

碩士學位論文 (初稿)

學 號:**M11207613**

****

**運用優先權與無耐性之區塊鏈交易模型研究**

**A Study on Blockchain Transaction Models with Priority and Impatience**

研 究 生： 蔡怡翔

指導教授： 鍾順平 博士

中華民國 一百一十四 年 七 月 二 日

**摘要**

本研究探討一個以區塊鏈為基礎的排隊系統，該系統在不同的使用者優先權與無耐性組合下，建構區塊鏈交易過程的數學模型，並引入開/關 (ON/OFF) 機制，以模擬區塊生成與共識階段的隨機可用性。系統由兩個串接的佇列構成：顧客佇列，客戶在此等待被打包進區塊；區塊佇列，已打包的客戶在此等待共識處理。系統採用部分批次服務機制進行區塊生成，其中允許不大於一最大數量的客戶可打包成一個區塊。在 OFF 狀態期間，區塊生成與共識作業會暫停，然而顧客到達仍持續進行，且若顧客佇列尚有容量，則新到達的客戶仍可進入排隊。

為深入描繪系統的行為與結構特性，本研究設計四種情境模型：（1）不具有無耐性的單一類型客戶、（2）不具有無耐性的雙類型客戶、（3）具有無耐性的單一類型客戶、（4）具有無耐性的雙類型客戶。針對每一情境，我們建構對應的多維馬可夫鏈來描述系統狀態，推導平衡方程並透過疊代方式求得穩態機率分布，進而計算多項效能指標，包括成功送達率、阻塞機率與平均等待時間。此外，本研究也探討不同參數對系統效能的影響。

為驗證解析結果，我們以 C++ 語言實現離散事件模擬，以忠實重現各情境中的事件邏輯與服務規則。模擬結果不僅驗證了解析結果的準確性，也揭示多項值得注意的系統行為，包括非搶佔優先權排程中公平性與效率的權衡、無耐性機制帶來的效能提升，以及部分批次機制與 ON/OFF 動態對整體系統表現的影響。

**關鍵字：區塊鏈、非搶佔優先權、無耐性、區塊生成、共識、部分批量服務、開/關機制**

# Abstract

This research investigates a blockchain-based queuing system that models the transaction process under varying combinations of customer priority and impatience, while incorporating ON/OFF mechanism to reflect the stochastic availability of block generation and the consensus phases. The system consists of two sequential queues: a customer queue, where customers wait to be grouped into a block, and a block queue, where grouped customers await consensus. A partial batch service mechanism is employed for block generation, allowing up to a maximum number of customers to be batched into a block. During OFF periods, block generation and consensus operations are suspended, although customer arrivals continue and are admitted into the customer queue if queue capacity is available.

To capture the behavioral and structural characteristics of the system, four distinct scenarios are modeled: (1) single-class customers without impatience, (2) two-class customers without impatience, (3) single-class customers with impatience, and (4) two-class customers with impatience. For each scenario, a multi-dimensional Markov chain is constructed to describe the system state. Balance equations are derived and solved iteratively to obtain the steady-state distribution, from which key performance metrics, including throughput, blocking probability, and average waiting times, are calculated. The effects of various parameters on the performance metrics are explored.

To validate the analytical results, a discrete-event simulation is implemented in C++, faithfully replicating the event logic and service rules of each scenario. The simulation results confirm the accuracy of analytical results and highlight several notable system behaviors, including the trade-off between fairness and efficiency in non-preemptive priority settings, the performance benefits introduced by impatience mechanisms, and the system-level effects of partial batch size and ON/OFF dynamics.

**Keywords: blockchain, non-preemptive priority, impatience, block generation, consensus, partial batch service, ON/OFF mechanism**

**Contents**

[**摘要** I](#_Toc201064950)

[Abstract III](#_Toc201064951)

[1. Introduction 1](#_Toc201064952)

[2. System Model 3](#_Toc201064953)

[2.1. Scenario 1: Single-Class Customers without Impatience 3](#_Toc201064954)

[2.2. Scenario 2: Two-Class Customers without Impatience 3](#_Toc201064955)

[2.3. Scenario 3: Single-Class Customers with Impatience 4](#_Toc201064956)

[2.4. Scenario 4: Two-Class Customers with Impatience 4](#_Toc201064957)

[3. Analytical Model 5](#_Toc201064958)

[3.1. Scenario 1: Single-Class Customer without Impatience 6](#_Toc201064959)

[3.1.1. State Balance Equations 7](#_Toc201064960)

[3.1.2. Iterative Algorithm 10](#_Toc201064961)

[3.1.3. Performance Measure 10](#_Toc201064962)

[3.2. Scenario 2: Two-Class Customer without Impatience 13](#_Toc201064963)

[3.2.1. State Balance Equations 13](#_Toc201064964)

[3.2.2. Iterative Algorithm 26](#_Toc201064965)

[3.2.3. Performance Measure 27](#_Toc201064966)

[3.3. Scenario 3: Single-Class Customer with Impatience 31](#_Toc201064967)

[3.3.1. State Balance Equations 31](#_Toc201064968)

[3.3.2. Iterative Algorithm 35](#_Toc201064969)

[3.3.1. Performance Measure 36](#_Toc201064970)

[3.4. Scenario 4: Two-Class Customer with Impatience 38](#_Toc201064971)

[3.4.1. State Balance Equations 39](#_Toc201064972)

[3.4.2. Iterative Algorithm 55](#_Toc201064973)

[3.4.3. Performance Measure 55](#_Toc201064974)

[4. Simulation Model 61](#_Toc201064975)

[4.1. Scenario 1: Single-Class Customer without Impatience 61](#_Toc201064976)

[4.1.1. Main program 62](#_Toc201064977)

[4.1.2. Arrival Subprogram 62](#_Toc201064978)

[4.1.3. Block Generation Subprogram 63](#_Toc201064979)

[4.1.4. Block Departure Subprogram 64](#_Toc201064980)

[4.1.5. Switch Subprogram 65](#_Toc201064981)

[4.1.6. Flowchart Diagram 66](#_Toc201064982)

[4.1.7. Performance Index 70](#_Toc201064983)

[4.2. Scenario 2: Two-Class Customer without Impatience 73](#_Toc201064984)

[4.2.1. Main program 73](#_Toc201064985)

[4.2.2. High-Priority Arrival Subprogram 74](#_Toc201064986)

[4.2.3. Low-Priority Arrival Subprogram 75](#_Toc201064987)

[4.2.4. Block Generation Subprogram 76](#_Toc201064988)

[4.2.5. Block Departure Subprogram 77](#_Toc201064989)

[4.2.6. Switch Subprogram 78](#_Toc201064990)

[4.2.7. Flowchart Diagram 80](#_Toc201064991)

[4.2.8. Performance Index 85](#_Toc201064992)

[4.3. Scenario 3: Single-Class Customer with Impatience 89](#_Toc201064993)

[4.3.1. Main program 89](#_Toc201064994)

[4.3.2. Arrival Subprogram 90](#_Toc201064995)

[4.3.3. Block Generation Subprogram 91](#_Toc201064996)

[4.3.4. Block Departure Subprogram 92](#_Toc201064997)

[4.3.5. Switch Subprogram 92](#_Toc201064998)

[4.3.6. Impatience subprogram 93](#_Toc201064999)

[4.3.7. Flowchart Diagram 95](#_Toc201065000)

[4.3.8. Performance Index 100](#_Toc201065001)

[4.4. Scenario 4: Two-Class Customer with Impatience 102](#_Toc201065002)

[4.4.1. Main program 103](#_Toc201065003)

[4.4.2. High-Priority Arrival Subprogram 103](#_Toc201065004)

[4.4.3. Low-Priority Arrival Subprogram 104](#_Toc201065005)

[4.4.4. Block Generation Subprogram 105](#_Toc201065006)

[4.4.5. Block Departure Subprogram 106](#_Toc201065007)

[4.4.6. Switch Subprogram 107](#_Toc201065008)

[4.4.7. Impatience subprogram 108](#_Toc201065009)

[4.4.8. Flowchart Diagram 110](#_Toc201065010)

[4.4.9. Performance Index 116](#_Toc201065011)

[5. Numerical Results 121](#_Toc201065012)

[5.1. Scenario 1: Single-Class Customer without Impatience 121](#_Toc201065013)

[5.1.1. Block size 121](#_Toc201065014)

[5.1.2. Arrival rate 126](#_Toc201065015)

[5.1.3. Block generation rate 131](#_Toc201065016)

[5.1.4. Consensus rate 136](#_Toc201065017)

[5.1.5. Transition rate (from ON to OFF) 141](#_Toc201065018)

[5.2. Scenario 2: Two-Class Customer without Impatience 146](#_Toc201065019)

[5.2.1. Block size 146](#_Toc201065020)

[5.2.2. Arrival rate 151](#_Toc201065021)

[5.2.3. Block generation rate 156](#_Toc201065022)

[5.2.4. Consensus rate 161](#_Toc201065023)

[5.2.5. Transition rate (ON to OFF) 166](#_Toc201065024)

[5.3. Scenario 3: Single-Class Customer with Impatience 171](#_Toc201065025)

[5.3.1. Block size 171](#_Toc201065026)

[5.3.2. Arrival rate 177](#_Toc201065027)

[5.3.3. Block generation rate 183](#_Toc201065028)

[5.3.4. Consensus rate 189](#_Toc201065029)

[5.3.5. Transition rate (from ON to OFF) 195](#_Toc201065030)

[5.3.6. Impatient rate 201](#_Toc201065031)

[5.4. Scenario 4: Two-Class Customer with Impatience 207](#_Toc201065032)

[5.4.1. Block size 207](#_Toc201065033)

[5.4.2. Arrival rate 214](#_Toc201065034)

[5.4.3. Block generation rate 221](#_Toc201065035)

[5.4.4. Consensus rate 228](#_Toc201065036)

[5.4.5. Transition rate (ON to OFF) 235](#_Toc201065037)

[5.4.6. Impatient rate 242](#_Toc201065038)

[6. Conclusion 249](#_Toc201065039)

[Reference 251](#_Toc201065040)

**List of Tables**

[Table 3‑1 The parameters used in different scenarios 6](#_Toc201063072)

**List of Figures**

[Figure 3‑1: System diagram 6](#_Toc201239662)

[Figure 3‑2: The state transition diagram of Case 11: 10](#_Toc201239663)

[Figure 3‑3: The state transition diagram of Case 45: 26](#_Toc201239664)

[Figure 3‑4: The state transition diagram of Case 12: 35](#_Toc201239665)

[Figure 3‑5: The state transition diagram of Case 45: 54](#_Toc201239666)

[Figure 4‑1: Flow chart of main program 66](#_Toc201239667)

[Figure 4‑2: Flow chart of arrival subprogram 67](#_Toc201239668)

[Figure 4‑3:Flow chart of block generation subprogram 68](#_Toc201239669)

[Figure 4‑4: Flow chart of block departure subprogram 69](#_Toc201239670)

[Figure 4‑5: Flow chart of switch subprogram 70](#_Toc201239671)

[Figure 4‑6: Flow chart of main program 80](#_Toc201239672)

[Figure 4‑7: Flow chart of HP arrival subprogram 81](#_Toc201239673)

[Figure 4‑8: Flow chart of LP arrival subprogram 82](#_Toc201239674)

[Figure 4‑9:Flow chart of block generation subprogram 83](#_Toc201239675)

[Figure 4‑10: Flow chart of block departure subprogram 84](#_Toc201239676)

[Figure 4‑11: Flow chart of switch subprogram 85](#_Toc201239677)

[Figure 4‑12: Flow chart of main program 95](#_Toc201239678)

[Figure 4‑13: Flow chart of arrival subprogram 96](#_Toc201239679)

[Figure 4‑14:Flow chart of block generation subprogram 97](#_Toc201239680)

[Figure 4‑15: Flow chart of block departure subprogram 98](#_Toc201239681)

[Figure 4‑16: Flow chart of switch subprogram 99](#_Toc201239682)

[Figure 4‑17: Flow chart of impatience subprogram 100](#_Toc201239683)

[Figure 4‑18: Flow chart of main program 110](#_Toc201239684)

[Figure 4‑19: Flow chart of HP arrival subprogram 111](#_Toc201239685)

[Figure 4‑20: Flow chart of LP arrival subprogram 112](#_Toc201239686)

[Figure 4‑21:Flow chart of block generation subprogram 113](#_Toc201239687)

[Figure 4‑22: Flow chart of block departure subprogram 114](#_Toc201239688)

[Figure 4‑23: Flow chart of switch subprogram 115](#_Toc201239689)

[Figure 4‑24: Flow chart of impatient subprogram 116](#_Toc201239690)

[Figure 5‑1: block size vs. average waiting time in the customer queue 123](#_Toc201239691)

[Figure 5‑2: Block size vs. average waiting time in the block queue 123](#_Toc201239692)

[Figure 5‑3: Block size vs. average waiting time in the system 124](#_Toc201239693)

[Figure 5‑4: Block size vs. average number of customers in block queue 124](#_Toc201239694)

[Figure 5‑5: Block size vs. blocking probability 125](#_Toc201239695)

[Figure 5‑6: Block size vs. system throughput 125](#_Toc201239696)

[Figure 5‑7: Arrival rate vs. average waiting time in the customer queue 128](#_Toc201239697)

[Figure 5‑8: Arrival rate vs. average waiting time in the block queue 128](#_Toc201239698)

[Figure 5‑9: Arrival rate vs. average waiting time in the system 129](#_Toc201239699)

[Figure 5‑10: Arrival rate vs. average number of customers in block queue 129](#_Toc201239700)

[Figure 5‑11: Arrival rate vs. blocking probability 130](#_Toc201239701)

[Figure 5‑12: Arrival rate vs. throughput 130](#_Toc201239702)

[Figure 5‑13: Block generation rate vs. average waiting time in the customer queue 133](#_Toc201239703)

[Figure 5‑14: Block generation rate vs. average waiting time in the block queue 133](#_Toc201239704)

[Figure 5‑15: Block generation rate vs. average waiting time in the system 134](#_Toc201239705)

[Figure 5‑16: Block generation rate vs. average number of customers in block queue 134](#_Toc201239706)

[Figure 5‑17: Block generation rate vs. blocking probability 135](#_Toc201239707)

[Figure 5‑18: Block generation rate vs. system throughput 135](#_Toc201239708)

[Figure 5‑19: Consensus rate vs. average waiting time in the customer queue 138](#_Toc201239709)

[Figure 5‑20: Consensus rate vs. average waiting time in the block queue 138](#_Toc201239710)

[Figure 5‑21: Consensus rate vs. average waiting time in the system 139](#_Toc201239711)

[Figure 5‑22: Consensus rate vs. average number of customers in block queue 139](#_Toc201239712)

[Figure 5‑23: Consensus rate vs. blocking probability 140](#_Toc201239713)

[Figure 5‑24: Consensus rate vs. system throughput 140](#_Toc201239714)

[Figure 5‑25: Transition rate vs. average waiting time in the customer queue in the system 143](#_Toc201239715)

[Figure 5‑26: Transition rate vs. average waiting time in the block queue 143](#_Toc201239716)

[Figure 5‑27: Transition rate vs. average waiting time in the system 144](#_Toc201239717)

[Figure 5‑28: Transition rate vs. average number of customers in block queue 144](#_Toc201239718)

[Figure 5‑29: Transition rate vs. blocking probability 145](#_Toc201239719)

[Figure 5‑30: Transition rate vs. system throughput 145](#_Toc201239720)

[Figure 5‑31: Block size vs. average waiting time in the customer queue 148](#_Toc201239721)

[Figure 5‑32: Block size vs. average waiting time in the block queue 148](#_Toc201239722)

[Figure 5‑33: Block size vs. average waiting time in the system 149](#_Toc201239723)

[Figure 5‑34: Block size vs. average number of customers in block queue 149](#_Toc201239724)

[Figure 5‑35: Block size vs. blocking probability 150](#_Toc201239725)

[Figure 5‑36: Block size vs. system throughput 150](#_Toc201239726)

[Figure 5‑37: HP arrival rate vs. average waiting time in the customer queue 153](#_Toc201239727)

[Figure 5‑38: HP arrival rate vs. average waiting time in the block queue 153](#_Toc201239728)

[Figure 5‑39: HP arrival rate vs. average waiting time in the system 154](#_Toc201239729)

[Figure 5‑40: HP arrival rate vs. average number of customers in block queue 154](#_Toc201239730)

[Figure 5‑41: HP arrival rate vs. blocking probability 155](#_Toc201239731)

[Figure 5‑42: HP arrival rate vs. throughput 155](#_Toc201239732)

[Figure 5‑43: HP block generation rate vs. average waiting time in the customer queue 158](#_Toc201239733)

[Figure 5‑44: HP block generation rate vs. average waiting time in the block queue 158](#_Toc201239734)

[Figure 5‑45: HP block generation rate vs. average waiting time in the system 159](#_Toc201239735)

[Figure 5‑46: HP block generation rate vs. average number of customers in block queue 159](#_Toc201239736)

[Figure 5‑47: HP block generation rate vs. blocking probability 160](#_Toc201239737)

[Figure 5‑48: HP block generation rate vs. system throughput 160](#_Toc201239738)

[Figure 5‑49: HP consensus rate vs. average waiting time in the customer queue 163](#_Toc201239739)

[Figure 5‑50: HP consensus rate vs. average waiting time in the block queue 163](#_Toc201239740)

[Figure 5‑51: HP consensus rate vs. average waiting time in the system 164](#_Toc201239741)

[Figure 5‑52: HP consensus rate vs. average number of customers in block queue 164](#_Toc201239742)

[Figure 5‑53: HP consensus rate vs. blocking probability 165](#_Toc201239743)

[Figure 5‑54: HP consensus rate vs. system throughput 165](#_Toc201239744)

[Figure 5‑55: Transition rate vs. average waiting time in the customer queue in the system 168](#_Toc201239745)

[Figure 5‑56: Transition rate vs. average waiting time in the block queue 168](#_Toc201239746)

[Figure 5‑57: Transition rate vs. average waiting time in the system 169](#_Toc201239747)

[Figure 5‑58: Transition rate vs. average number of customers in block queue 169](#_Toc201239748)

[Figure 5‑59: Transition rate vs. blocking probability 170](#_Toc201239749)

[Figure 5‑60: Transition rate vs. system throughput 170](#_Toc201239750)

[Figure 5‑61: Block size vs. average waiting time in the customer queue 173](#_Toc201239751)

[Figure 5‑62: Block size vs. average waiting time in the block queue 173](#_Toc201239752)

[Figure 5‑63: Block size vs. average waiting time in the system 174](#_Toc201239753)

[Figure 5‑64: Block size vs. average number of customers in block queue 174](#_Toc201239754)

[Figure 5‑65: Block size vs. blocking probability 175](#_Toc201239755)

[Figure 5‑66: Block size vs. system throughput 175](#_Toc201239756)

[Figure 5‑67: Block size vs. the impatient probability 176](#_Toc201239757)

[Figure 5‑68: Arrival rate vs. average waiting time in the customer queue 179](#_Toc201239758)

[Figure 5‑69: Arrival rate vs. average waiting time in the block queue 179](#_Toc201239759)

[Figure 5‑70: Arrival rate vs. average waiting time in the system 180](#_Toc201239760)

[Figure 5‑71: Arrival rate vs. average number of customers in block queue 180](#_Toc201239761)

[Figure 5‑72: Arrival rate vs. blocking probability 181](#_Toc201239762)

[Figure 5‑73: Arrival rate vs. throughput 181](#_Toc201239763)

[Figure 5‑74: Arrival rate vs. the impatient probability 182](#_Toc201239764)

[Figure 5‑75: Block generation rate vs. average waiting time in the customer queue 185](#_Toc201239765)

[Figure 5‑76: Block generation rate vs. average waiting time in the block queue 185](#_Toc201239766)

[Figure 5‑77: Block generation rate vs. average waiting time in the system 186](#_Toc201239767)

[Figure 5‑78: Block generation rate vs. average number of customers in block queue 186](#_Toc201239768)

[Figure 5‑79: Block generation rate vs. blocking probability 187](#_Toc201239769)

[Figure 5‑80: Block generation rate vs. system throughput 187](#_Toc201239770)

[Figure 5‑81: Effect of block generation on the impatient probability 188](#_Toc201239771)

[Figure 5‑82: Consensus rate vs. average waiting time in the customer queue 191](#_Toc201239772)

[Figure 5‑83: Consensus rate vs. average waiting time in the block queue 191](#_Toc201239773)

[Figure 5‑84: Consensus rate vs. average waiting time in the system 192](#_Toc201239774)

[Figure 5‑85: Consensus rate vs. average number of customers in block queue 192](#_Toc201239775)

[Figure 5‑86: Consensus rate vs. blocking probability 193](#_Toc201239776)

[Figure 5‑87: Consensus rate vs. system throughput 193](#_Toc201239777)

[Figure 5‑88: Consensus rate vs. the impatient probability 194](#_Toc201239778)

[Figure 5‑89: Transition rate vs. average waiting time in the customer queue in the system 197](#_Toc201239779)

[Figure 5‑90: Transition rate vs. average waiting time in the block queue 197](#_Toc201239780)

[Figure 5‑91: Transition rate vs. average waiting time in the system 198](#_Toc201239781)

[Figure 5‑92: Transition rate vs. average number of customers in block queue 198](#_Toc201239782)

[Figure 5‑93: Transition rate vs. blocking probability 199](#_Toc201239783)

[Figure 5‑94: Transition rate vs. system throughput 199](#_Toc201239784)

[Figure 5‑95: Transition rate vs. the impatient probability 200](#_Toc201239785)

[Figure 5‑96: Impatient rate vs. average waiting time in the customer queue in the system 203](#_Toc201239786)

[Figure 5‑97: Impatient rate vs. average waiting time in the block queue 203](#_Toc201239787)

[Figure 5‑98: Impatient rate vs. average waiting time in the system 204](#_Toc201239788)

[Figure 5‑99: Impatient rate vs. average number of customers in block queue 204](#_Toc201239789)

[Figure 5‑100: Impatient rate vs. blocking probability 205](#_Toc201239790)

[Figure 5‑101: Impatient rate vs. system throughput 205](#_Toc201239791)

[Figure 5‑102: Impatient rate vs. the impatient probability 206](#_Toc201239792)

[Figure 5‑103: Block size vs. average waiting time in the customer queue 210](#_Toc201239793)

[Figure 5‑104: Block size vs. average waiting time in the block queue 210](#_Toc201239794)

[Figure 5‑105: Block size vs. average waiting time in the system 211](#_Toc201239795)

[Figure 5‑106: Block size vs. average number of customers in block queue 211](#_Toc201239796)

[Figure 5‑107: Block size vs. blocking probability 212](#_Toc201239797)

[Figure 5‑108: Block size vs. system throughput 212](#_Toc201239798)

[Figure 5‑109: Block size vs. the impatient probability 213](#_Toc201239799)

[Figure 5‑110: HP arrival rate vs. average waiting time in the customer queue 217](#_Toc201239800)

[Figure 5‑111: HP arrival rate vs. average waiting time in the block queue 217](#_Toc201239801)

[Figure 5‑112: HP arrival rate vs. average waiting time in the system 218](#_Toc201239802)

[Figure 5‑113: HP arrival rate vs. average number of customers in block queue 218](#_Toc201239803)

[Figure 5‑114: HP arrival rate vs. blocking probability 219](#_Toc201239804)

[Figure 5‑115: HP arrival rate vs. throughput 219](#_Toc201239805)

[Figure 5‑116: HP arrival rate vs. the impatient probability 220](#_Toc201239806)

[Figure 5‑117: HP block generation rate vs. average waiting time in the customer queue 224](#_Toc201239807)

[Figure 5‑118: HP block generation rate vs. average waiting time in the block queue 224](#_Toc201239808)

[Figure 5‑119: HP block generation rate vs. average waiting time in the system 225](#_Toc201239809)

[Figure 5‑120: HP block generation rate vs. average number of customers in block queue 225](#_Toc201239810)

[Figure 5‑121: HP block generation rate vs. blocking probability 226](#_Toc201239811)

[Figure 5‑122: HP block generation rate vs. system throughput 226](#_Toc201239812)

[Figure 5‑123: HP block generation rate vs. the impatient probability 227](#_Toc201239813)

[Figure 5‑124: HP consensus rate vs. average waiting time in the customer queue 231](#_Toc201239814)

[Figure 5‑125: HP consensus rate vs. average waiting time in the block queue 231](#_Toc201239815)

[Figure 5‑126: HP consensus rate vs. average waiting time in the system 232](#_Toc201239816)

[Figure 5‑127: HP consensus rate vs. average number of customers in block queue 232](#_Toc201239817)

[Figure 5‑128: HP consensus rate vs. blocking probability 233](#_Toc201239818)

[Figure 5‑129: HP consensus rate vs. system throughput 233](#_Toc201239819)

[Figure 5‑130: HP consensus rate vs. the impatient probability 234](#_Toc201239820)

[Figure 5‑131: Transition rate vs. average waiting time in the customer queue in the system 238](#_Toc201239821)

[Figure 5‑132: Transition rate vs. average waiting time in the block queue 238](#_Toc201239822)

[Figure 5‑133: Transition rate vs. average waiting time in the system 239](#_Toc201239823)

[Figure 5‑134: Transition rate vs. average number of customers in block queue 239](#_Toc201239824)

[Figure 5‑135: Transition rate vs. blocking probability 240](#_Toc201239825)

[Figure 5‑136: Transition rate vs. system throughput 240](#_Toc201239826)

[Figure 5‑137: Transition rate vs. the impatient probability 241](#_Toc201239827)

[Figure 5‑138: Impatient rate vs. average waiting time in the customer queue in the system 244](#_Toc201239828)

[Figure 5‑139: Impatient rate vs. average waiting time in the block queue 244](#_Toc201239829)

[Figure 5‑140: Impatient rate vs. average waiting time in the system 245](#_Toc201239830)

[Figure 5‑141: Impatient rate vs. average number of customers in block queue 245](#_Toc201239831)

[Figure 5‑142: Impatient rate vs. blocking probability 246](#_Toc201239832)

[Figure 5‑143: Impatient rate vs. system throughput 246](#_Toc201239833)

[Figure 5‑144: Impatient rate vs. the impatient probability 247](#_Toc201239834)

# Introduction

Blockchain technology, first proposed by Nakamoto in 2008, has rapidly evolved into a foundational infrastructure for digital trust and decentralized systems. As a form of distributed ledger technology (DLT), blockchain is characterized by decentralization, transparency, and immutability, making it particularly suited for secure data storage and peer-to-peer value transfer. Each block contains a hash of the previous block, a timestamp, and a collection of transactions, forming an append-only chain that is nearly impossible to tamper with. Originally designed to support cryptocurrencies like Bitcoin, blockchain has since been adopted in numerous domains including finance, healthcare, media, logistics, and energy.

One of the most pressing technical challenges in today’s blockchain landscape is interoperability, that is the ability for independently operated blockchain networks to communicate and exchange assets or information. This challenge has spurred the development of cross-chain bridges, which act not as physical connections but rather as a collection of protocols and mechanisms that allow heterogeneous blockchains to interoperate. These bridges enable asset transfers, data exchange, and coordinated smart contract execution between public chains, consortium chains, and private chains, which are otherwise isolated due to architectural and consensus differences. Similar concerns have also emerged in layered edge-cloud systems, where performance evaluation frameworks are often built on queueing-theoretic modeling.

To address the performance analysis of blockchain systems, a number of prior works have employed queueing theory to model system dynamics under realistic assumptions. For instance, researchers have simulated edge-cloud offloading networks using M/G/1 and M/G/m models to assess task delays and system throughput in blockchain-based layered environments [1]. Another study applied M/M/n/L queues to model transaction processing and block generation in Bitcoin, demonstrating how queue length and block production rates impact performance [2].

In more structured systems such as Hyperledger Fabric, a queueing network model was proposed to divide the consensus process into execution, ordering, and validation stages, enabling analysis of latency across phases [3]. Other researchers combined queueing models with multidimensional Markov chains to analyze PBFT-based consensus systems with repairable voting nodes, quantifying system reliability and throughput under dynamic conditions [4]. Performance bottlenecks in Fabric’s architecture were also identified via benchmarking, helping guide practical optimizations [5].

Beyond consensus mechanics, theoretical models have captured the growth dynamics and reward allocation strategies in multi-mining pool environments such as Ethereum. One study introduced a tree-based blockchain structure and renewal reward theory to model stale and uncle blocks [6]. Priority-based transaction handling has also been modeled using non-preemptive limited-priority queues, illustrating the performance tradeoffs between high- and low-priority transaction classes [7]. To tackle intractable steady-state distributions in complex systems, another approach applied the maximum entropy principle to estimate probabilities based on observable statistics, providing flexible approximations without strong distributional assumptions [8].

In response to the lack of simple yet effective models for analyzing cross-chain systems, this thesis draws on examples from [9] and [10] to develop a queueing model for cross-chain transaction flows. The model abstracts the system into two sequential queues: the customer queue, where transactions wait to be selected for block formation, and the block queue, where blocks undergo consensus. To better capture realistic customer behavior, the model considers multiple user classes with non-preemptive limited priority and partial batch service, as well as system states that alternate between ON and OFF. User impatience is also incorporated to reflect transaction abandonment in highly congested environments. These dynamics are analyzed across four scenarios: (1) single-class customers without impatience, (2) two-class customers without impatience, (3) single-class customers with impatience, and (4) two-class customers with impatience.

To evaluate the system's steady-state behavior under complex configurations, this thesis adopts a numerical iteration method based on the balance equations of the underlying Markov chain. A simulation is also performed for validation. This approach enables the computation of key performance metrics.

This thesis proceeds as follows. Chapter 2 introduces the system model, detailing the cross-chain process structure and the queuing assumptions used in this study. Chapter 3 presents the analytical model, which formalizes the system behavior under various parameter settings and derives key performance metrics. Chapter 4 describes the simulation model, providing implementation details and simulation strategies used to validate the analytical results. Chapter 5 reports the numerical results and performance evaluation across the proposed scenarios. Finally, Chapter 6 concludes the thesis and outlines potential directions for future work.

# System Model

We aim to study four blockchain scenarios, each involving two queues of finite capacity: the customer queue and the block queue. The maximum capacity of the customer queue is denoted by , while the block queue, which represents the stage where users participate the consensus after being grouped into a block, has a capacity of . Customers in the system first wait in the customer queue for the block generation process. Once this process is complete, a group of customers is moved to the block queue to undergo the consensus process.

The blocking generation process is based on a partial batch service mechanism. When the block queue becomes idle, if there are more than customers in the customer queue, the first customers are selected and moved to the block queue. If there are or fewer customers waiting, all of them are transferred instead. After the consensus process finishes, regardless of whether the result is successful, all customers in the block queue leave the system. The performance of the system depends on the balance between the effective service rate () and the effective arrival rate ().

Additionally, the system may switch between ON and OFF periods. During the OFF period, caused by events such as hacking attacks or connection failures due to environmental factors, both the block generation and consensus processes are suspended. Once the system returns to the ON period, these processes resume as usual.

## Scenario 1: Single-Class Customers without Impatience

In the first scenario, we assume that there is only a single class of customers in the system, and the queueing discipline for the customer queue is First-Come-First-Served (FCFS). It is noted that if the block queue is empty, at most customers can wait in the customer queue for the block generation process. On the other hand, if the block queue is not empty, the maximum capacity of customers allowed in the customer queue is reduced to .

## Scenario 2: Two-Class Customers without Impatience

In the second scenario, we assume that there are two classes of customers in the system: HP (high-priority) customers and LP (low-priority) customers. Customers with the same priority are served according to the First-Come-First-Served (FCFS) discipline. Note that for HP customers are always placed ahead of LP customers in the customer queue. Customers with different priorities are served according to the non-preemptive priority discipline. Specifically, HP customers are always placed ahead of LP customers in the customer queue and the consensus process of the LP customers cannot be interrupted. Note that for HP customers, the maximum capacity of the customer queue is when the block queue is idle, and when it is not idle. On the other hand, for LP customers, the maximum capacity of the customer queue is always , regardless of whether the block queue is idle or not.

## Scenario 3: Single-Class Customers with Impatience

The third scenario considers a single class of customers with impatience. Customers still follow the First-Come-First-Served (FCFS) discipline, but they may leave the system while waiting in the customer queue if their waiting time exceeds their patience threshold. Once a customer enters the block queue, impatience is no longer considered. It is noted that if the block queue is empty, at most customers can wait in the customer queue for the block generation process. On the other hand, if the block queue is not empty, the maximum capacity of customers allowed in the customer queue is reduced to .

## Scenario 4: Two-Class Customers with Impatience

In the fourth scenario, we again consider two classes of customers, which HP and LP customers, with impatience. Customers of the same priority follow the First-Come-First-Served (FCFS) discipline, and customers of different priorities follow the non-preemptive discipline, i.e., HP customers are given precedence over LP customers in the queue and the consensus process of the LP customers cannot be interrupted. Customers from both priority classes may leave the queue if they wait too long. Each priority class may have its own impatience rate. Impatience is no longer relevant once customers enter the block queue. Note that for HP customers, the maximum capacity of the customer queue is when the block queue is idle, and when it is not idle. On the other hand, for LP customers, the maximum capacity of the customer queue is always , regardless of whether the block queue is idle or not.

# Analytical Model

In this chapter, we are going to present four different scenarios for modeling blockchain-based systems: (1) single-class customers without impatience, (2) two-class customers without impatience, (3) single-class customers with impatience, and (4) two-class customers with impatience. Each of these scenarios is built upon a queuing-based abstraction of the blockchain process and aims to capture distinct behavioral features related to customer priority and abandonment. In all cases, as shown in Figure 3‑1, the system is composed of two queues with limited capacity: the customer queue, which temporarily holds customers before block generation, and the block queue, which represents the stage where customers participate in the consensus protocol after being grouped into a block.

Assume that the arrivals of customers follow a Poisson process, where the arrival rate is denoted by . In the multi-class scenarios, we further distinguish between HP and LP customers, whose respective arrival rates are and , so that the total arrival rate satisfies . After arriving at the customer queue, customers wait for the block generation process, and the duration of that process is determined by an exponential distribution with a rate of (or and in the two-class case). Once a block is formed, a group of customers is transferred to the block queue, where the consensus process is carried out and the duration of that process is determined by an exponential distribution at a service rate denoted by (or and depending on customer class).

In scenarios that involve impatience, we assume that customers may abandon the system while waiting in the customer queue if their waiting time exceeds a certain threshold. The impatience threshold is modeled as an exponential random variable with a rate for single-class customers, and rates and for HP and LP customers, respectively. Once a customer enters the block queue, impatience is no longer considered. In addition, we consider the operational reliability of the system by incorporating the possibility of the system state alternating between ON and OFF periods. During ON periods, both block generation and consensus operations are allowed to proceed, while during OFF periods, these operations are suspended. The durations of both ON and OFF periods are exponentially distributed. The transition rates between the two states are given by (ON to OFF) and (OFF to ON) respectively.



Figure 3‑1: System diagram

We assume the queueing discipline is First-Come-First-Served (FCFS) for customers of the same class. In the two-class scenarios, customers are additionally scheduled under a non-preemptive priority rule, in which HP customers are placed ahead of LP ones in the customer queue, but once a customer enters the block queue, their service cannot be interrupted. These settings allow us to examine the interplay between system structure, service prioritization, impatience-driven abandonment, and queue dynamics in a blockchain-inspired environment. The parameters used in different scenarios are shown in Table 3.1

|  |  |  |
| --- | --- | --- |
| Description | Single-class | Two-class |
| Arrival rate |  |  |
|  |
| Block generation rate |  |  |
|  |
| Consensus rate |  |  |
|  |
| Impatient rate |  |  |
|  |
| Transition rate (ON to OFF) |  |  |
| Transition rate (OFF to ON) |  |  |

Table ‑ The parameters used in different scenarios

## Scenario 1: Single-Class Customer without Impatience

In this scenario, we consider a single-class customer system without impatience, where arrivals follow a Poisson process and customers are served based on the First-Come-First-Served (FCFS) discipline. The service process is divided into block generation and consensus phases, and the system switches between ON and OFF states, affecting service availability.

Assume that the arrivals of customers follow a Poisson process, where the arrival rate is denoted by λ. After arriving at the customer queue, customers wait for the block generation process, which occurs at a rate of . Each block is generated according to the partial batch policy, i.e., each block can contain 1 to customers. Once a block is formed, a group of customers is transferred to the block queue, where the consensus process is carried out at a service rate denoted by .

In addition, we consider the operational reliability of the system by incorporating the possibility of the system state alternating between ON and OFF periods. During ON periods, both block generation and consensus operations are allowed to proceed, while during OFF periods, these operations are suspended. The durations of both ON and OFF periods are exponentially distributed. The transition rates from ON to OFF and from OFF to ON are given by and , respectively.

The and of this scenario is:

|  |  |  |
| --- | --- | --- |
|  |  | (‑) |
|  |  | (‑) |

### State Balance Equations

The system under consideration is described as a three-dimensional Markov chain with state denoted by , where denotes the number of customers in the customer queue, denotes the number of customers in the block queue, and denotes the system state. When , the maximum capacity of customers in the customer queue is . When , meaning that the block queue is occupied, the maximum capacity of customers allowed in the customer queue is reduced to . The system state indicates that the system is in the ON state, where customers can enter the customer queue and both block generation and consensus operations can proceed. On the other hand, when , the system is in the OFF state, during which only customer arrivals to the queue are permitted, while block generation and consensus are suspended. The state space can be denoted as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (‑) |

Hence, the total number of feasible states is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (‑) |

For example, if and , the number of feasible states is 1182. The steady state probability of state is denoted as . In this scenario, the feasible states can be categorized into 16 distinct cases, as described below.

#### System off,

##### 

##### 

##### 

##### 

##### 

##### 

#### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

Given the large number of equations presented above, it is impractical to illustrate all the corresponding state transition diagrams. Therefore, we focus on a relatively complex case, specifically Case 11, as a representative example, shown in Figure 3‑2.

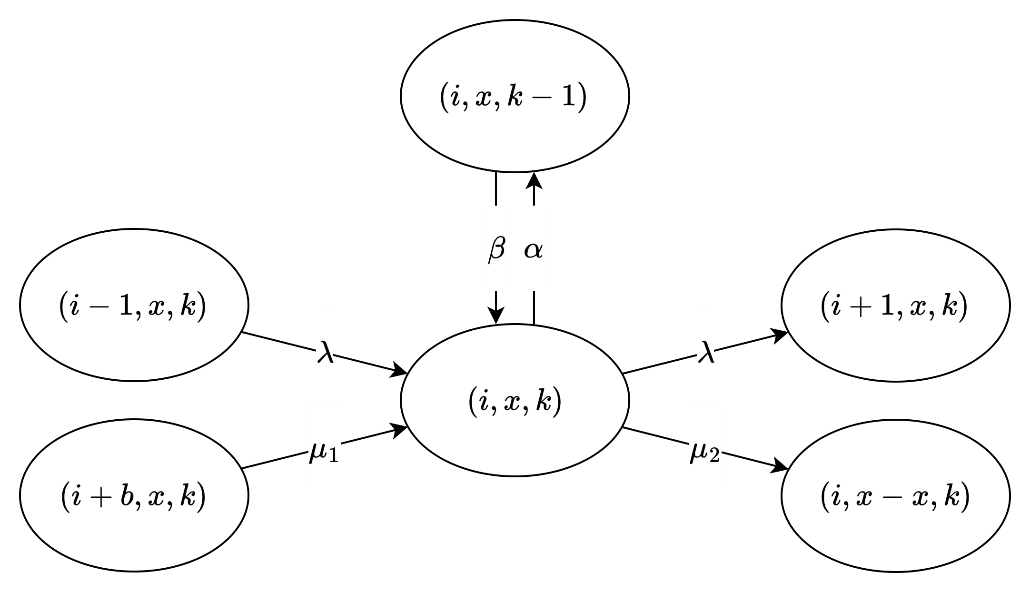


Figure 3‑2: The state transition diagram of Case 11:

### Iterative Algorithm

We use the iterative algorithm provided below, and perform calculations on the state balance equations until they converge, allowing us to determine the steady-state distribution of the system.

###### Iterative algorithm:

**Step 1**: Initialize for all , where is the total number of feasible states.

**Step 2**: Substitute into the balance equations from Case 1 to Case 99 to find , .

**Step 3**: Normalize , .

**Step 4**: If , then stop the iteration. Otherwise, set , , and return to **Step 2**.

In our analysis, the convergence threshold is set to , and the algorithm typically converges after about 75 iterations.

### Performance Measure

After obtaining the steady-state probabilities through the iterative algorithm, we proceed to compute several performance metrics to evaluate the effectiveness of the system.

First of all, the average number of customers in the whole system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (‑) |

Second, the average number of customers in customer queue, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (‑) |

Third, the average number of customers in block queue, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑7) |

Fourth, the blocking probability of the system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑8) |

Fifth, the throughput of the system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑9) |

Sixth, the average waiting time in the system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑10) |

Seventh, the average waiting time in the customer queue, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑11) |

Eighth, the average waiting time in the block queue, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑12) |

Finally, the average number of blocks participating in the consensus process per unit of time, denoted by , is given below.

|  |  |  |
| --- | --- | --- |
|  |  | (3‑13) |

## Scenario 2: Two-Class Customer without Impatience

In this scenario, we consider a two-class customer system without impatience, where the arrivals of HP and LP customers follow the independent Poisson processes, with arrival rates denoted by and , respectively. Customers in this scenario are served based on the non-preemptive priority discipline, where HP customers are placed ahead of LP ones in the customer queue, but ongoing service cannot be interrupted.

The service process is divided into block generation and consensus phases. After arriving at the customer queue, customers wait for the block generation process, which occurs at a rate of and for HP and LP customers, respectively. Each block is generated according to the partial batch policy, i.e., each block can contain 1 to customers of the same policy class. Once a block is formed, it is transferred to the block queue, where the consensus process is carried out at the service rate denoted by and for HP and LP customers, respectively.

In addition, we consider the operational reliability of the system by incorporating the possibility of the system state alternating between ON and OFF periods. During ON periods, both block generation and consensus operations are allowed to proceed, while during OFF periods, these operations are suspended. The durations of both ON and OFF periods are exponentially distributed. The transition rates from ON to OFF and from OFF to ON are given by and , respectively.

The and of this scenario is:

|  |  |  |
| --- | --- | --- |
|  |  | (‑) |
|  |  | (‑) |

### State Balance Equations

The system under consideration is described as a five-dimensional Markov chain denoted by , where and represent the number of HP and LP customers in the customer queue, respectively. and represent the number of HP and LP customers in the block queue, respectively. And denotes the system state. When the block queue is empty (i.e., and ), the maximum capacity of customers allowed in the customer queue is , implying that . However, when the block queue is occupied (i.e., or ), the maximum capacity of customers in the customer queue is reduced to , and thus .

Customers are scheduled according to the non-preemptive priority discipline, where HP customers are always placed ahead of LP ones in the queue, but service already in progress cannot be interrupted. When a block is generated, it must contain customer(s) of only one priority class, and is transferred into the block queue as a batch for processing without preemption.

The system state indicates that the system is in the ON state, where customers can enter the customer queue and both block generation and consensus operations can proceed. On the other hand, when , the system is in the OFF state, during which only customer arrivals to the queue are permitted, while block generation and consensus are suspended. The state space can be denoted as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑16) |

Hence, the total number of feasible states is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑17) |

For example, if and , the number of feasible states is 22524. The steady state probability of state is denoted as . In this scenario, the feasible states can be categorized into 99 distinct cases, as described below.

#### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

#### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

#### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

#### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

#### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

#### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

#### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

#### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

Given the large number of equations presented above, it is impractical to illustrate all the corresponding state transition diagrams. Therefore, we focus on a relatively complex case, specifically Case 45, as a representative example, shown in Figure 3‑3.

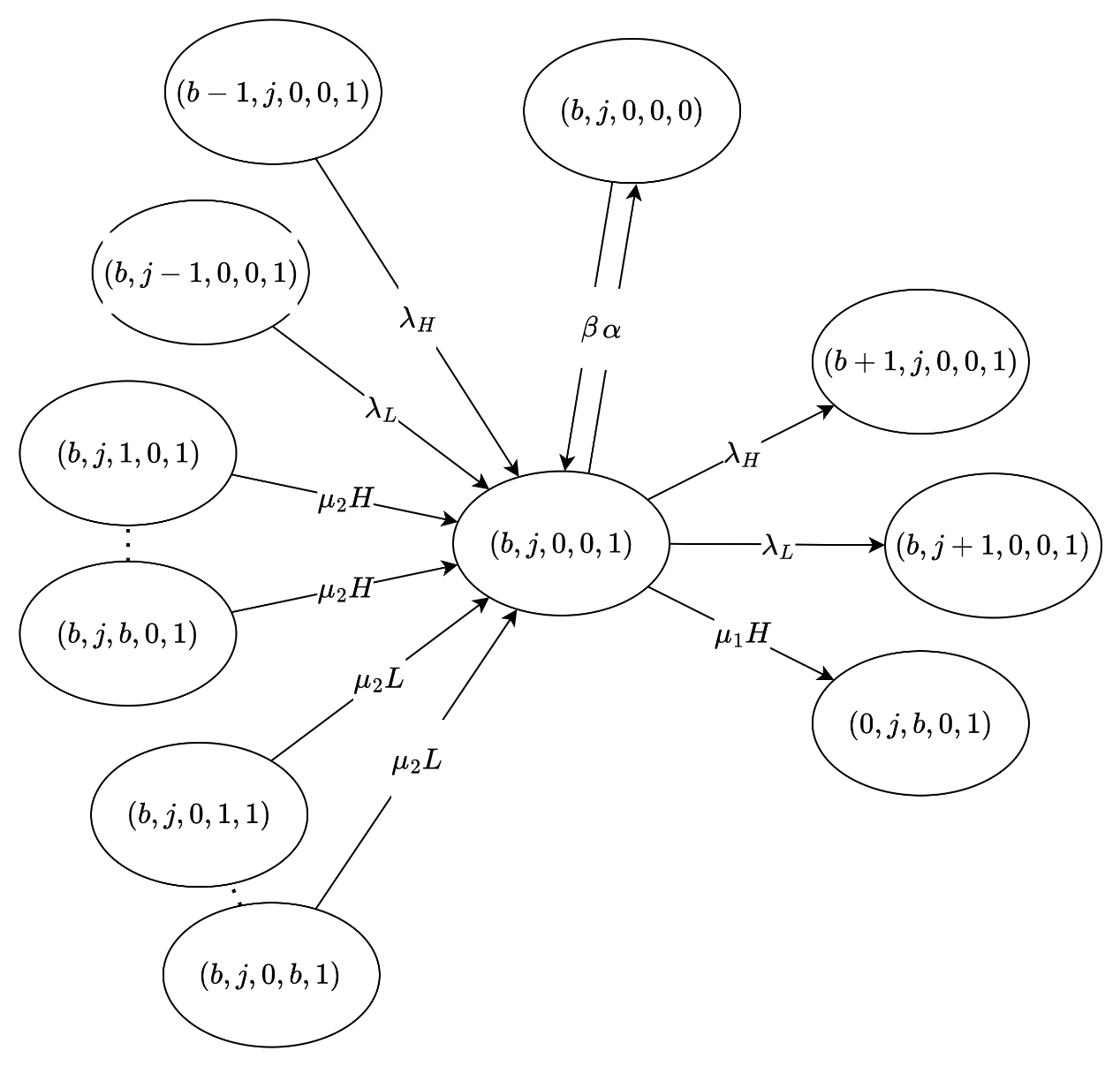
****

Figure 3‑3: The state transition diagram of Case 45:

### Iterative Algorithm

We use the iterative algorithm provided below, and perform calculations on the state balance equations until they converge, allowing us to determine the steady-state distribution of the system.

###### Iterative algorithm:

**Step 1**: Initialize for all , where is the total number of feasible states.

**Step 2**: Substitute into the balance equations from Case 1 to Case 99 to find , ..

**Step 3**: Normalize , .

**Step 4**: If , then stop the iteration. Otherwise, set , ., and return to **Step 2**.

In our analysis, the convergence threshold is set to , and the algorithm typically converges after about 80 iterations.

### Performance Measure

After obtaining the steady-state probabilities through the iterative algorithm, we proceed to compute several performance metrics to evaluate the effectiveness of the system.

First of all, the average number of HP and LP customers in the whole system, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑18) |
|  |  | (3‑19) |

The average number of customers in the whole system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑20) |

Second, the average number of HP and LP customers in customer queue, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑21) |
|  |  | (3‑22) |

The average number of customers in customer queue, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑23) |

Third, the average number of HP and LP customers in block queue, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑24) |
|  |  | (3‑25) |

The average number of customers in block queue, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑26) |

Fourth, the blocking probability of HP and LP customers in the system, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑27) |
|  |  | (3‑28) |

The blocking probability of the system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑29) |

Fifth, the throughput of HP and LP customers in the system, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑30) |
|  |  | (3‑31) |

The throughput of the system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑32) |

Sixth, the average waiting time of the HP and LP customers in the system, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑33) |
|  |  | (3‑34) |

The average waiting time in the system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑35) |

Seventh, the average waiting time of the HP and LP customers in the customer queue, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑36) |
|  |  | (3‑37) |

The average waiting time in the customer queue, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑38) |

Eighth, the average waiting time of the HP and LP customers in the block queue, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑39) |
|  |  | (3‑40) |

The average waiting time in the block queue, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑41) |

Finally, the average number of HP and LP blocks participating in the consensus process, denoted by and , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑42) |
|  |  | (3‑43) |

The average number of blocks participating in the consensus process per unit of time, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑44) |

## Scenario 3: Single-Class Customer with Impatience

In this scenario, we consider a single-class customer system with impatience, where arrivals follow a Poisson process and customers are served based on the First-Come-First-Served (FCFS) discipline. The service process is divided into block generation and consensus phases, and the system switches between ON and OFF states, affecting service availability.

Assume that the arrivals of customers follow a Poisson process, where the arrival rate is denoted by λ. After arriving at the customer queue, customers wait for the block generation process, which occurs at a rate of . Each block is generated according to the partial batch policy, i.e., each block can contain 1 to customers. Once a block is formed, a group of customers is transferred to the block queue, where the consensus process is carried out at a service rate denoted by .

To account for customer impatience, we assume that customers in the customer queue may leave the system if they wait too long. The patience time is assumed to follow an exponential distribution, with impatience rates denoted by . Customers in the block queue are assumed to be committed and will not abandon once service has started.

In addition, we consider the operational reliability of the system by incorporating the possibility of the system state alternating between ON and OFF periods. During ON periods, both block generation and consensus operations are allowed to proceed, while during OFF periods, these operations are suspended. The durations of both ON and OFF periods are exponentially distributed. The transition rates from ON to OFF and from OFF to ON are given by and , respectively.

The and of this scenario is shown as below, which :

|  |  |  |
| --- | --- | --- |
|  |  | (‑) |
|  |  | (‑) |

### State Balance Equations

The system under consideration is described as a three-dimensional Markov chain with state denoted by , where denotes the number of customers in the customer queue, denotes the number of customers in the block queue, and denotes the system state. When , the maximum capacity of customers in the customer queue is . When , meaning that the block queue is occupied, the maximum capacity of customers allowed in the customer queue is reduced to .

In this scenario, customers may abandon the customer queue if their waiting time exceeds a certain threshold. The patience time is assumed to follow an exponential distribution with rate , and abandonment occurs only while the customer is waiting in the customer queue.

The system state indicates that the system is in the ON state, where customers can enter the customer queue and both block generation and consensus operations can proceed. On the other hand, when , the system is in the OFF state, during which only customer arrivals to the queue are permitted, while block generation and consensus are suspended. The state space can be denoted as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑47) |

Hence, the total number of feasible states is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑48) |

For example, if and , the number of feasible states is 1182. The steady state probability of state is denoted as . In this scenario, the feasible states can be categorized into 16 distinct cases, as described below.

#### System off,

##### 

##### 

##### 

##### 

##### 

##### 

#### System on,

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

Given the large number of equations presented above, it is impractical to illustrate all the corresponding state transition diagrams. Therefore, we focus on a relatively complex case, specifically Case 12, as a representative example, shown in Figure 3‑4.

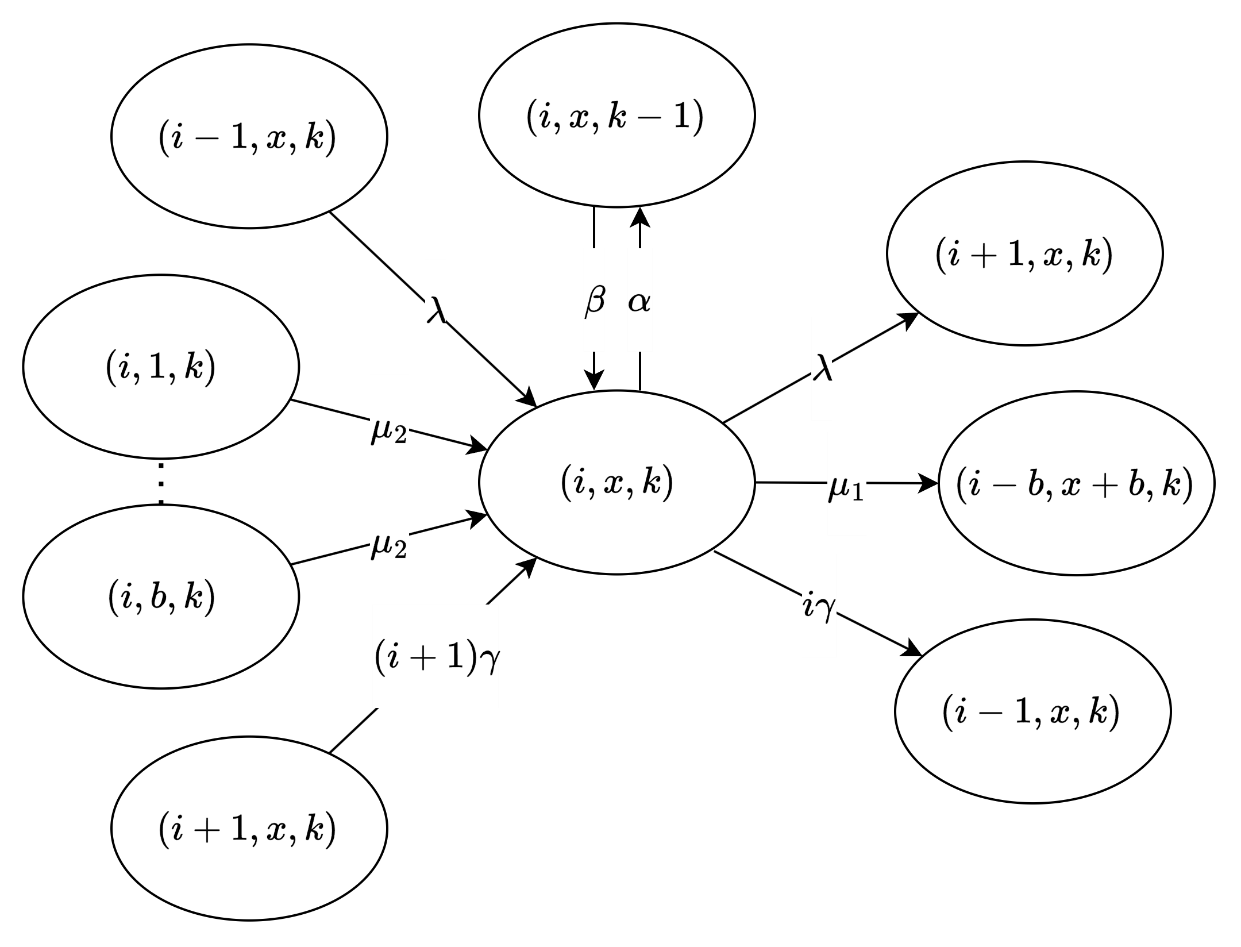


Figure 3‑4: The state transition diagram of Case 12:

### Iterative Algorithm

We use the iterative algorithm provided below, and perform calculations on the state balance equations until they converge, allowing us to determine the steady-state distribution of the system.

###### Iterative algorithm:

**Step 1**: Initialize for all , where is the total number of feasible states.

**Step 2**: Substitute into the balance equations from Case 1 to Case 16 to find , .

**Step 3**: Normalize , .

**Step 4**: If , then stop the iteration. Otherwise, set , , and return to **Step 2**.

In our analysis, the convergence threshold is set to , and the algorithm typically converges after about 72 iterations.

### Performance Measure

After obtaining the steady-state probabilities through the iterative algorithm, we proceed to compute several performance metrics to evaluate the effectiveness of the system.

First of all, the average number of customers in the whole system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑49) |

Second, the average number of customers in customer queue, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑50) |

Third, the average number of customers in block queue, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑51) |

Fourth, the blocking probability of the system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑52) |

Fifth, the impatient probability of the system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑53) |

Sixth, the throughput of the system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑54) |

Seventh, the average waiting time in the customer queue, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑55) |

Eighth, the average waiting time in the block queue, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑56) |

Ninth, the average waiting time in the system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑57) |

Finally, the average number of blocks participating in the consensus process per unit of time, denoted by , is given below.

|  |  |  |
| --- | --- | --- |
|  |  | (3‑58) |

## Scenario 4: Two-Class Customer with Impatience

In this scenario, we consider a two-class customer system without impatience, where the arrivals of HP and LP customers follow the independent Poisson processes, with arrival rates denoted by and , respectively. Customers in this scenario are served based on the non-preemptive priority discipline, where HP customers are placed ahead of LP ones in the customer queue, but ongoing service cannot be interrupted.

The service process is divided into block generation and consensus phases. After arriving at the customer queue, customers wait for the block generation process, which occurs at a rate of and for HP and LP customers, respectively. Each block is generated according to the partial batch policy, i.e., each block can contain 1 to customers of the same policy class. Once a block is formed, it is transferred to the block queue, where the consensus process is carried out at the service rate denoted by and for HP and LP customers, respectively.

To account for customer impatience, we assume that customers in the customer queue may leave the system if they wait too long. The patience time is assumed to follow an exponential distribution, with impatience rates​ and ​ for HP and LP customers, respectively. Customers in the block queue are assumed to be committed and will not abandon once service has started.

In addition, we consider the operational reliability of the system by incorporating the possibility of the system state alternating between ON and OFF periods. During ON periods, both block generation and consensus operations are allowed to proceed, while during OFF periods, these operations are suspended. The durations of both ON and OFF periods are exponentially distributed. The transition rates from ON to OFF and from OFF to ON are given by and , respectively.

The and of this scenario is shown as below, which :

|  |  |  |
| --- | --- | --- |
|  |  | (‑) |
|  |  | (‑) |

### State Balance Equations

The system under consideration is described as a five-dimensional Markov chain denoted by , where and represent the number of HP and LP customers in the customer queue, respectively. and represent the number of HP and LP customers in the block queue, respectively. And denotes the system state. When the block queue is empty (i.e., and ), the maximum capacity of customers allowed in the customer queue is , implying that . However, when the block queue is occupied (i.e., or ), the maximum capacity of customers in the customer queue is reduced to , and thus .

Customers are scheduled according to the non-preemptive priority discipline, where HP customers are always placed ahead of LP ones in the queue, but service already in progress cannot be interrupted. When a block is generated, it must contain customer(s) of only one priority class, and is transferred into the block queue as a batch for processing without preemption.

The system state indicates that the system is in the ON state, where customers can enter the customer queue and both block generation and consensus operations can proceed. On the other hand, when , the system is in the OFF state, during which only customer arrivals to the queue are permitted, while block generation and consensus are suspended. The state space can be denoted as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑61) |

Hence, the total number of feasible states is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑62) |

For example, if and , the number of feasible states is 22524. The steady state probability of state is denoted as . In this scenario, the feasible states can be categorized into 99 distinct cases, as described below.

#### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

#### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

#### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

##### 

Given the large number of equations presented above, it is impractical to illustrate all the corresponding state transition diagrams. Therefore, we focus on a relatively complex case, specifically Case 45, as a representative example, shown in Figure 3‑5.

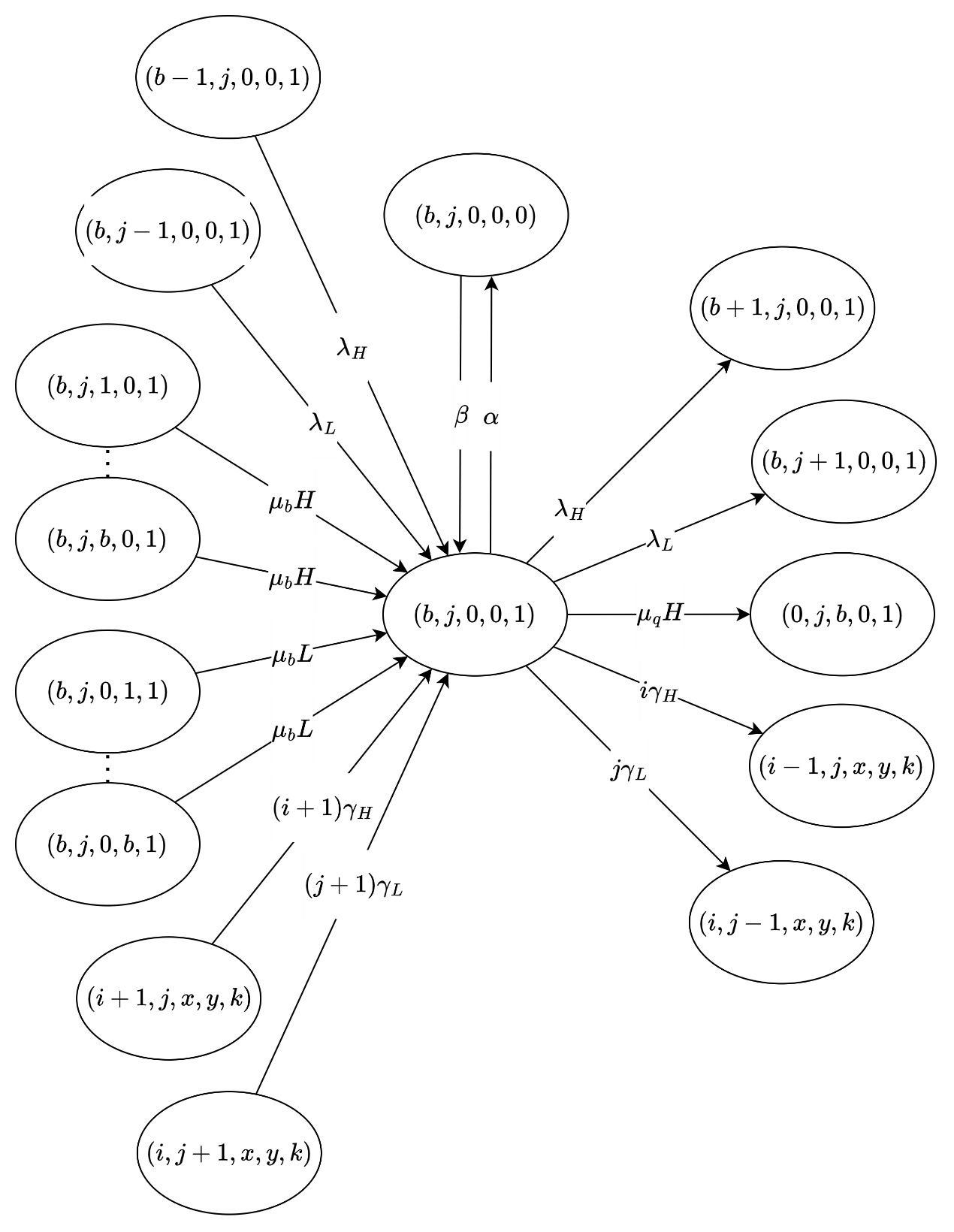


Figure 3‑5: The state transition diagram of Case 45:

### Iterative Algorithm

We use the iterative algorithm provided below, and perform calculations on the state balance equations until they converge, allowing us to determine the steady-state distribution of the system.

###### Iterative algorithm:

**Step 1**: Initialize for all , where is the total number of feasible states.

**Step 2**: Substitute into the balance equations from Case 1 to Case 99 to find , ..

**Step 3**: Normalize , .

**Step 4**: If , then stop the iteration. Otherwise, set , ., and return to **Step 2**.

In our analysis, the convergence threshold is set to , and the algorithm typically converges after about 80 iterations.

### Performance Measure

After obtaining the steady-state probabilities through the iterative algorithm, we proceed to compute several performance metrics to evaluate the effectiveness of the system.

First of all, the average number of HP and LP customers in the whole system, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑63) |
|  |  | (3‑64) |

The average number of customers in the whole system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑65) |

Second, the average number of HP and LP customers in customer queue, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑66) |
|  |  | (3‑67) |

The average number of customers in customer queue, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑68) |

Third, the average number of HP and LP customers in block queue, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑69) |
|  |  | (3‑70) |

The average number of customers in block queue, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑71) |

Fourth, the blocking probability of HP and LP customers in the system, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑72) |
|  |  | (3‑73) |

The blocking probability of the system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑74) |

Fifth, the impatient probability of HP and LP customers in the system, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑75) |
|  |  | (3‑76) |

The impatient probability of the system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑77) |

Sixth, the throughput of HP and LP customers in the system, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑78) |
|  |  | (3‑79) |

The throughput of the system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑80) |

Seventh, the average waiting time of the HP and LP customers in the customer queue, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑81) |
|  |  | (3‑82) |

The average waiting time in the customer queue, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑83) |

Eighth, the average waiting time of the HP and LP customers in the block queue, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑84) |
|  |  | (3‑85) |

The average waiting time in the block queue, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑86) |

Ninth, the average waiting time of the HP and LP customers in the system, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑87) |
|  |  | (3‑88) |

The average waiting time in the block queue, denoted by is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑89) |

Finally, the average number of HP and LP blocks participating in the consensus process, denoted by and , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑90) |
|  |  | (3‑91) |

The average number of blocks participating in the consensus process per unit of time, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3‑92) |

# Simulation Model

In this chapter, we present a detailed explanation of four simulation scenarios, each corresponding to a different configuration of blockchain queueing behavior. These scenarios are designed to reflect the structural and behavioral differences introduced by customer priority and impatience. All simulation models incorporate both First-Come-First-Served (FCFS) and non-preemptive priority disciplines, as appropriate to each case.

The first simulation model represents a single-class customer system without impatience. In this case, customers arrive and are served strictly in arrival order, and no abandonment occurs even if the waiting time is long. The second simulation model introduces two customer classes, HP and LP, handled with non-preemptive scheduling but without impatience. HP customers are always placed ahead of LP customers in the queue, but service-in-progress of any customer cannot be interrupted.

The third simulation model considers a single-class system with impatience, where customers may abandon the queue if they wait too long. This adds a stochastic abandonment dynamic based on patience thresholds. The final simulation model incorporates both customer priority and impatience. HP and LP customers are managed with non-preemptive priority, and both classes have their own impatience rates. This complex setting allows us to examine how prioritization and abandonment interact in a congested blockchain environment.

In all cases, the simulation captures system dynamics under partial batch service, and models ON/OFF channel behavior, where the service is suspended during OFF periods. These scenarios are simulated independently to compare their performance metrics, including throughput, queue lengths, waiting time, blocking probability, and, where applicable, abandonment probability.

## Scenario 1: Single-Class Customer without Impatience

In this simulation model, we consider a blockchain system that handles a single class of customers, where customers arrive according to a Poisson process and are served under the First-Come-First-Served (FCFS) discipline.

The system consists of two queues: the customer queue, where customers wait for block generation, and the block queue, where customers participate in the consensus process after being grouped into a block. Block generation follows a partial batch service policy, allowing 1 to customers to form a block. Once a block is formed, it is transferred to the block queue. Upon completion of the consensus process, all customers in the block exit the system.

During the OFF state, caused by interruptions such as attacks or connectivity issues, both block generation and consensus processes are suspended, although new customers may still arrive and be admitted. During the ON state, all services resume normally. To preserve system integrity, a constraint is imposed on the maximum number of customers allowed in the customer queue: when the block queue is empty, up to customers may wait; otherwise, the limit is reduced to .

Since customer impatience is not considered in this model, all customers remain in the queue until they are served. This makes the first scenario a baseline case for performance comparison, focusing on metrics such as throughput, average queue length, and system utilization under a stable environment with uninterrupted customer service.

### Main program

The main program executes a series of steps to simulate the blockchain queuing system, illustrated in Figure 4‑1. At the beginning of each simulation run, all relevant variables are initialized. This includes resetting statistical parameters, setting the next block generation time and next departure time to infinity, marking the channel status as ON, initializing the block generation status as idle, and setting the customer queue limit to .

Next, the system parameters are configured. These include the maximum customer queue capacity (), the maximum number of customers per block (), the arrival rate (), the block generation rate (), the consensus rate (), and the ON/OFF switching rates ( and ) for the system channel.

The program generates the next arrival time and channel switch time using exponential random variables based on the corresponding system parameters. During the simulation, it compares the scheduled times of four events and selects the earliest event to execute its corresponding subprogram.

Finally, a while loop is used to repeat the simulation until a predefined number of customer arrivals has been reached. Once this condition is met, the simulation terminates and the performance statistics are output.

### Arrival Subprogram

Figure 4.2 illustrated the flow chart of the arrival subprogram, simulates the arrival of a new customer to the system. Upon invocation, the total number of arrivals is incremented, and the simulation time is updated to the scheduled arrival time. The time for the next arrival is then scheduled using an exponential interarrival time generated with the arrival rate . Then, the area calculation function is invoked to update all time-averaged statistics based on the elapsed time since the last event.

Next, the system checks whether the customer queue has reached its capacity limit.

* If the queue is full, the arriving customer is rejected, and the number of rejections is incremented.
* If the queue is not full, the arriving customer is admitted. In this case, both the number of customers in the system and in the queue are incremented, and the customer's arrival time is recorded in the queue log.

Finally, the system determines whether to initiate block generation:

* If the channel status is in ON state, and block generator is idle, and this customer is the only one in the queue, a new block generation event is scheduled based on an exponential random variable with rate .
* If the block generator is busy or the channel is OFF, the next block generation time is set to infinity to suspend the process.

### Block Generation Subprogram

Figure 4‑3 illustrates the flow chart of the block generation subprogram, which simulates the initiation of a block generation process. When this event is triggered, the simulation time is updated to the scheduled block generation time. Then, the area calculation function is invoked to update all time-averaged statistics based on the elapsed time since the last event.

Next, the block generator status is set to busy, indicating that a block is currently being generated. To ensure sufficient space for the upcoming consensus process, the capacity limit of the customer queue is reduced from to , where is the maximum number of customers allowed in a block.

The system then determines how many customers should be transferred from the queue into the block:

* If more than customers are waiting in the queue, exactly are selected.
* Otherwise, all remaining customers in the queue are moved into the block.

The number of customers transferred into the block is recorded, and the queue size is adjusted accordingly. A block departure event is then scheduled based on an exponential random variable with rate . After this, the next block generation time is set to infinity to prevent immediate retriggering.

For each customer that enters the block, their corresponding arrival time is logged into the block log. These timestamps are subsequently used to compute the cumulative queueing time. This calculation is performed using the total waiting time function, which sums the time differences between the current simulation time and each customer's original queue entry time.

Finally, the corresponding entries in the queue log are removed to reflect that these customers have exited the queue and are now participating in the consensus process.

### Block Departure Subprogram

Figure 4‑4 illustrates the flow chart of the departure subprogram, which simulates the completion of a block consensus process. When this event is triggered, the simulation time is updated to the scheduled block departure time. Then, the area calculation function is invoked to update all time-averaged statistics based on the elapsed time since the last event.

At this point, the block generation status is reset to idle, and the customer queue capacity limit is restored to its original value , allowing the queue to accept new customers at full capacity. The block departure event is considered completed and is therefore cleared.

The program then calculates the total time that the current block of customers spent in the consensus stage. This is achieved using the block time accumulation function, which computes the total time difference between the current simulation time and each customer's recorded entry into the block.

After consensus completion, the number of customers currently in the system is decreased by the number of customers in the departing block, and the total number of customers served is incremented accordingly. The block is now empty, and all associated entries in the block log are removed.

Finally, if there are still customers waiting in the queue, a new block generation event is scheduled based on an exponential random variable with rate .

### Switch Subprogram

Figure 4‑5 illustrates the flow chart of the switch subprogram, which simulates the transition of the system between ON and OFF states. When this event is triggered, the simulation time is updated to the scheduled switch time. Then, the area calculation function is invoked to update all time-averaged statistics based on the elapsed time since the last event.

The system channel status is then toggled as follows:

* **If the system transitions from ON to OFF:**
  + The channel status is set to OFF.
  + The next switch event is scheduled based on an exponential random variable with rate (representing the OFF duration).
  + All ongoing service operations are suspended by setting both the block generation and block departure event times to infinity.
* **If the system transitions from OFF to ON:**
  + The channel status is set to ON.
  + The next switch event is scheduled based on an exponential random variable with rate (representing the ON duration).
  + If there is at least one customer in the queue and the block generator is currently idle:
    - A block generation event is scheduled based on an exponential random variable with rate .
  + If a block in consensus phase is suspended:
    - A block departure event is scheduled using an exponential random variable with rate .

Through this subprogram, the simulation captures the stochastic availability of the system by alternating between operational and suspended phases, reflecting real-world unreliability such as downtime or external disruptions. During the ON period, block generation and consensus operations proceed as normal. During the OFF period, these processes are temporarily halted while new customer arrivals may still occur.

### Flowchart Diagram



Figure ‑: Flow chart of main program

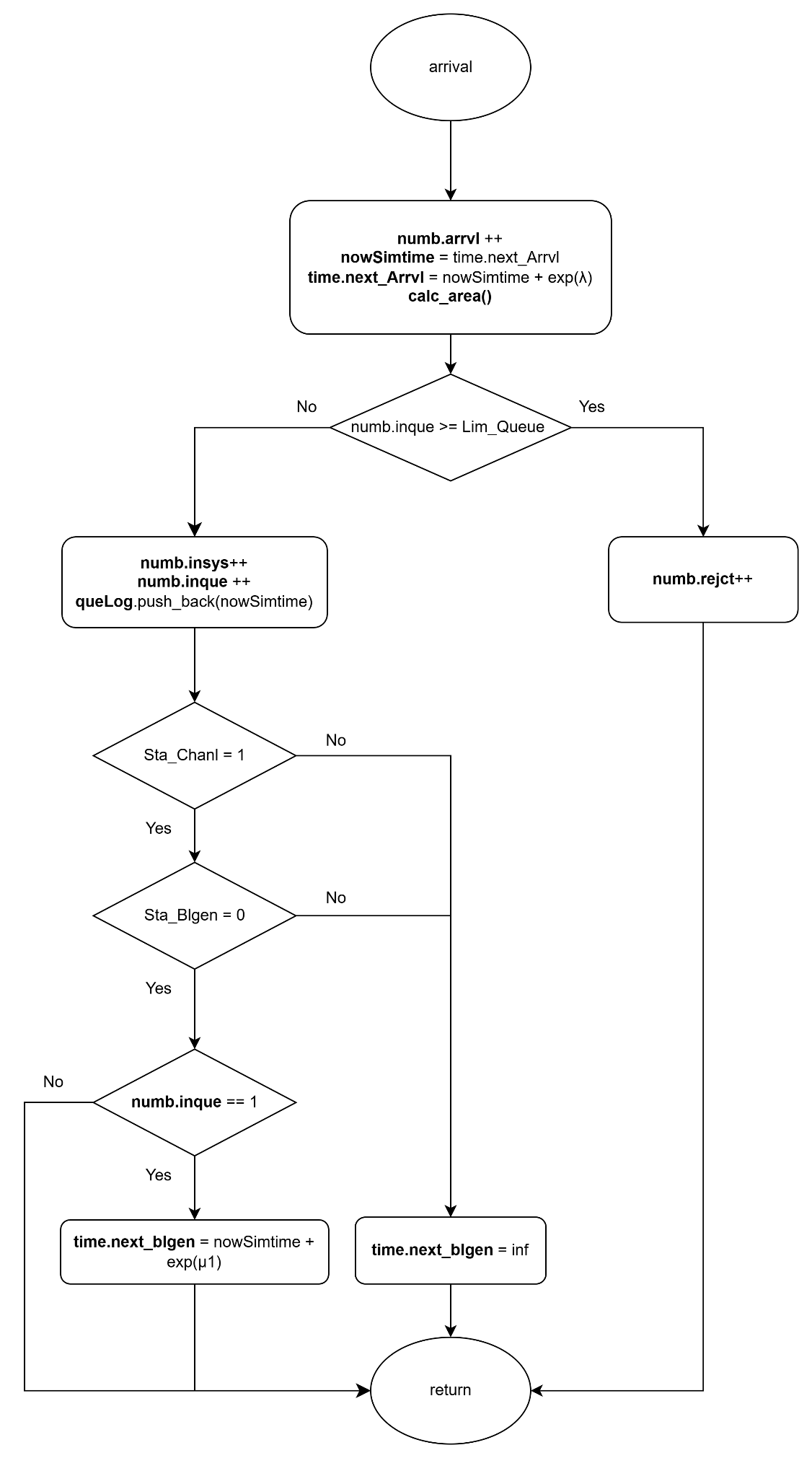


Figure ‑: Flow chart of arrival subprogram

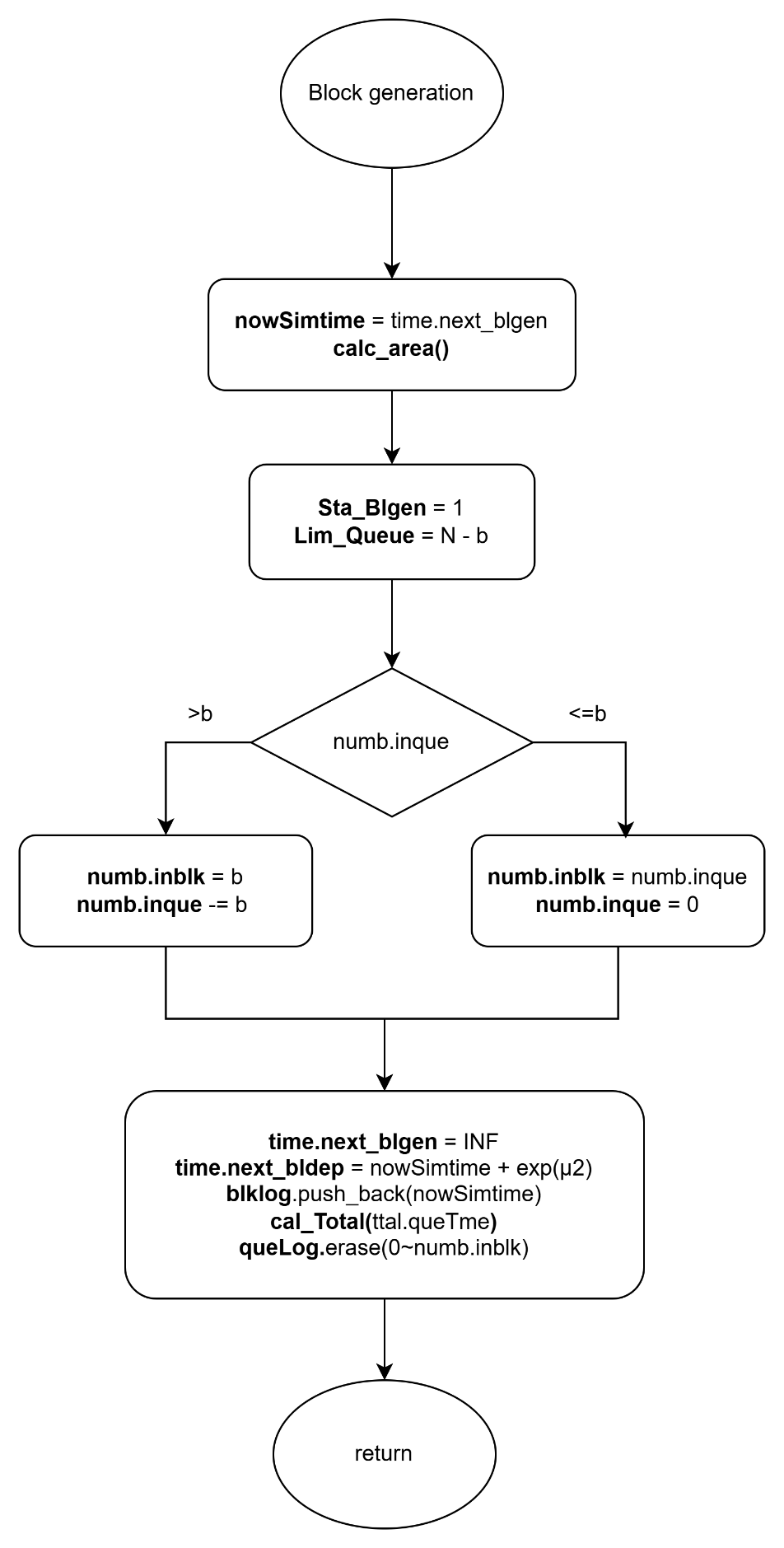


Figure ‑:Flow chart of block generation subprogram

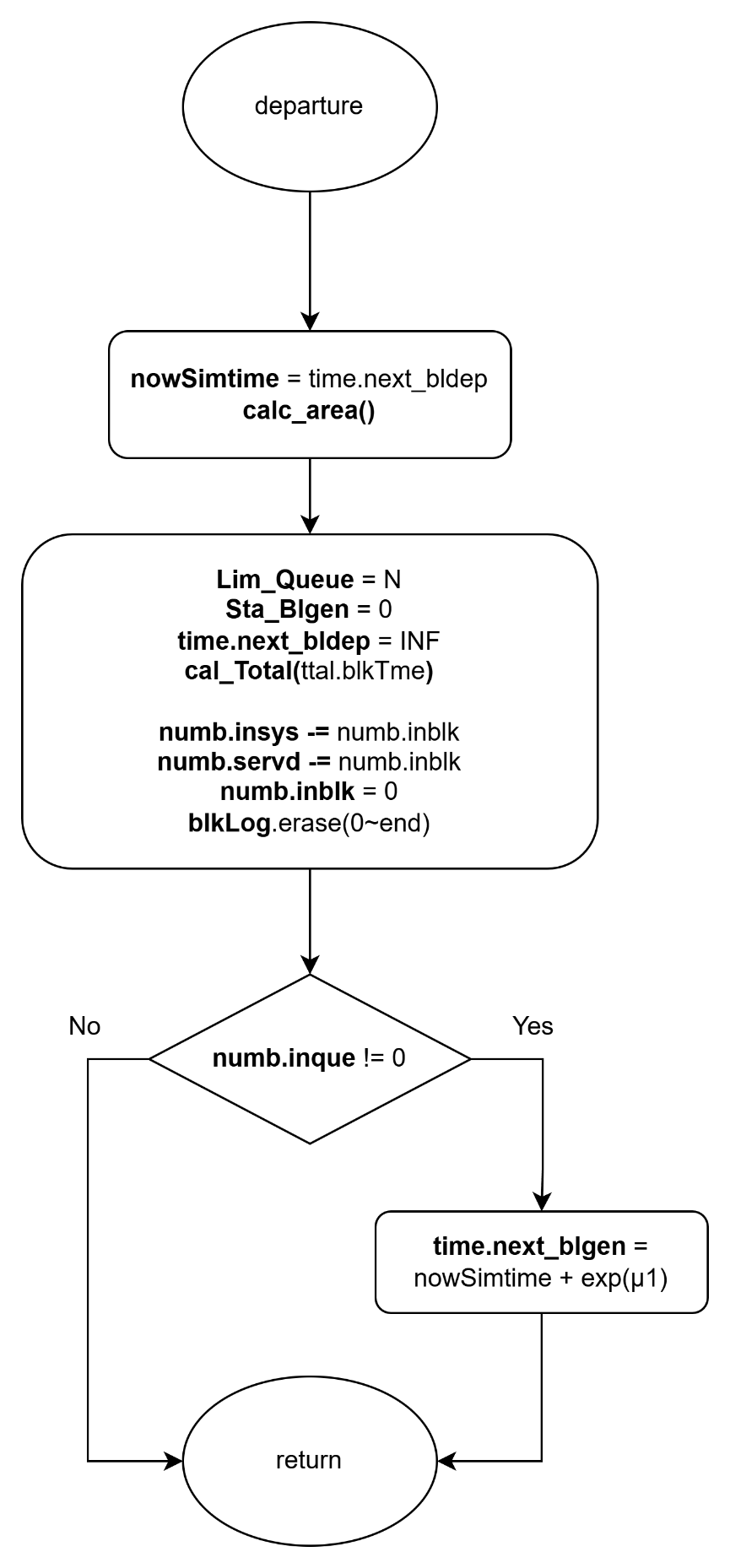


Figure ‑: Flow chart of block departure subprogram

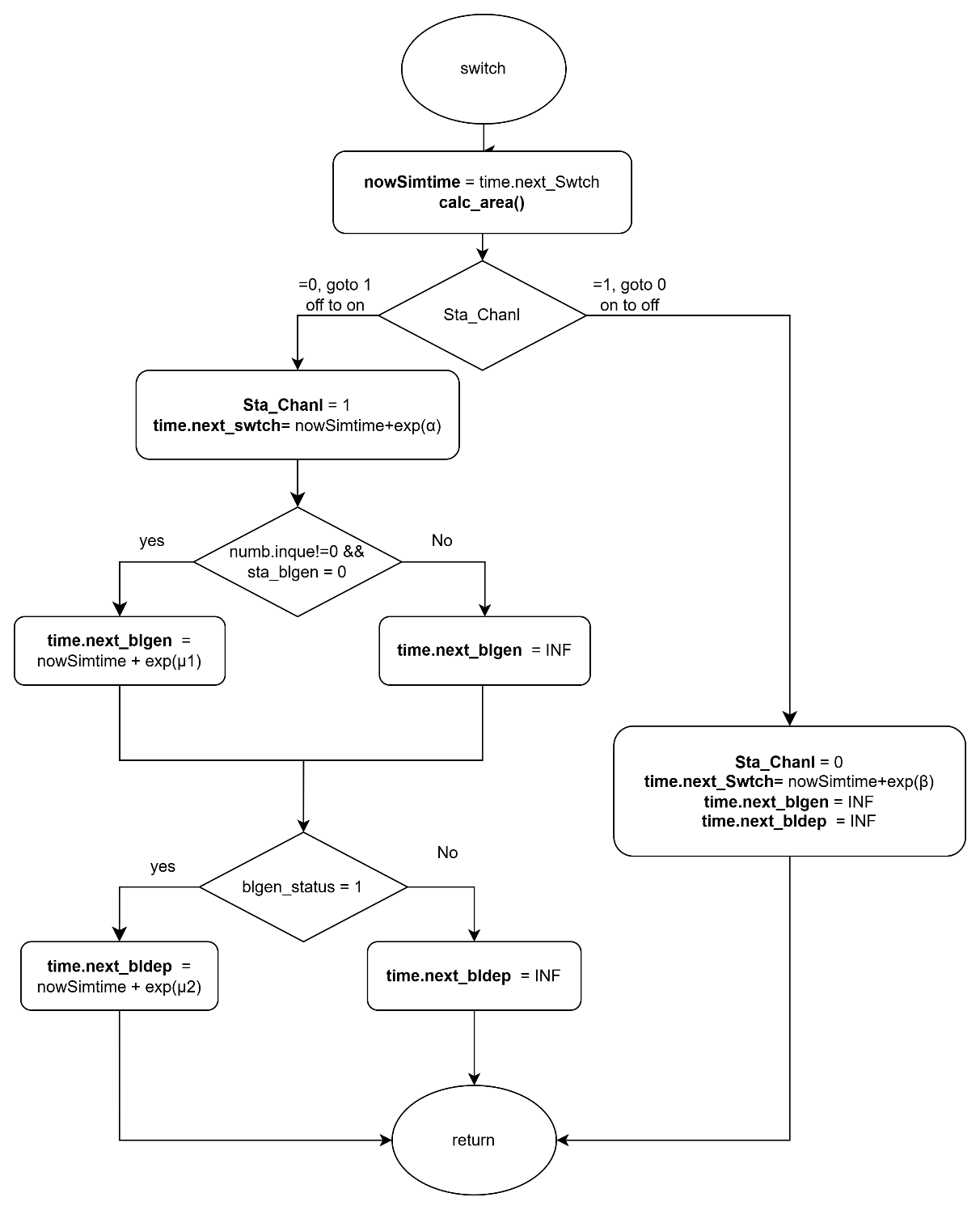


Figure ‑: Flow chart of switch subprogram

### Performance Index

To evaluate the system’s performance, we compute several performance indices based on the simulated results obtained from the simulation.

First of all, the average number of customers in the whole system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑1) |

Second, the average number of customers in customer queue, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑2) |

Third, the average number of customers in block queue, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑3) |

Fourth, the blocking probability of the system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑4) |

Fifth, the throughput of the system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑5) |

Sixth, the average waiting time in the system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑6) |

Seventh, the average waiting time in the customer queue, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑7) |

Eighth, the average waiting time in the block queue, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑8) |

Finally, the average number of blocks participating in the consensus process per unit of time, denoted by , is given below.

|  |  |  |
| --- | --- | --- |
|  |  | (4‑9) |

## Scenario 2: Two-Class Customer without Impatience

In this simulation model, we consider a blockchain system that handles two classes of customers: HP and LP customers. Customers of different priorities arrive according to an independent Poisson process, and customers of the same priority are served under the First-Come-First-Served (FCFS) discipline. Customers of different priorities are handled using a non-preemptive priority rule, where HP customers are always placed ahead of LP customers in the queue, but ongoing service for a LP block cannot be interrupted once initiated.

The system consists of two queues: the customer queue and the block queue. HP and LP customers both enter the customer queue upon arrival if possible. Block generation follows a partial batch service policy and operates on customers of only one priority class at a time. Each block can include at most customers. Once a block that is composed solely of HP or LP customer(s) is formed, it is transferred to the block queue. After completing the consensus process, all customers in the block exit the system.

The system alternates between ON and OFF periods to reflect external interruptions such as cyberattacks or connection failures. During the OFF state, both block generation and consensus process are suspended, though new customers may still arrive and be queued. During the ON state, all services resume as normal.

To preserve system integrity and fairness, different queue capacity constraints apply based on customer class and system state. For HP customers, the maximum number allowed in the customer queue is when the block queue is empty, and when it is occupied. For LP customers, the customer queue capacity is always limited to , regardless of the block queue state.

Since this model does not include customer impatience, all arriving customers remain in the system until they are served. This scenario is designed to study the impact of non-preemptive priority scheduling on performance, focusing on metrics such as per-class throughput, queue length, and system utilization under stable yet priority-sensitive operation.

### Main program

The main program executes a series of steps to simulate the blockchain queuing system with two classes of customers, as illustrated in Figure 4‑6. At the beginning of each simulation run, all relevant variables are initialized. This includes resetting statistical parameters, setting the next block generation time and next departure time to infinity, marking the channel status as ON, initializing the block generation status as idle, and setting the customer queue limit to .

Next, the system parameters are configured. These include the maximum customer queue capacity (), the maximum number of customers per block (), the arrival rates for HP and LP customers ( and ), the block generation rates ( and ), the consensus rates ( and ), and the ON/OFF switching rates ( and ) for the system channel.

The program then generates the next arrival times for both HP and LP customers, as well as the channel switch time, using exponential random variables based on the corresponding system parameters. During the simulation, it compares the scheduled times of five events and selects the earliest event to execute its corresponding subprogram.

Finally, a while loop is used to repeat the simulation until a predefined number of customer arrivals has been reached. Once this condition is met, the simulation terminates and the performance statistics are output.

### High-Priority Arrival Subprogram

As illustrated in Figure 4‑7, the HP arrival subprogram simulates the arrival of a HP customer to the system. When this event is triggered, the simulation time is updated to the current arrival time. The arrival counters are incremented to reflect both the total number of customers and the number of HP arrivals. The next arrival event for HP customers is then scheduled based on an exponential random variable with rate . Immediately after, the area calculation function is invoked to update all time-averaged statistics based on the elapsed time since the last event.

Next, the system checks whether the customer queue has reached its capacity limit.

* If the queue is full, the arriving customer is rejected. In this case, both the total number of rejections and the number of HP rejections are incremented.
* If the queue is not full, the arriving customer is admitted. The number of customers in the system and in the queue are both incremented, along with their corresponding HP counts. The arrival time of the customer is recorded in the HP queue log.

Then, the system updates the unified queue log by merging the HP and LP arrival records, ensuring that HP entries appear first. The system then sets the priority flag to indicate that HP customers are currently at the head of the queue.

Finally, the system determines whether to initiate block generation:

* If the channel status is in ON state, and block generator is idle, and this customer is the only one in the queue, a new block generation event is scheduled based on an exponential random variable with rate .
* If the block generator is busy or the channel is OFF, the next block generation time is set to infinity to suspend the process.

### Low-Priority Arrival Subprogram

As illustrated in Figure 4‑8, the LP subprogram simulates the arrival of a LP customer to the system. When this event is triggered, the simulation time is updated to the scheduled arrival time. The arrival counters are incremented to reflect both the total number of customers and the number of LP arrivals.

The next arrival event for LP customers is then scheduled based on an exponential random value with the rate . Then, the area calculation function is invoked to update all time-averaged statistics based on the elapsed time since the last event.

Next, the system checks whether the customer queue has reached its capacity limit. The rejection condition depends on the system’s block generation state:

* If the number of LP customers in the queue has reached , or
* The total number of customers in the queue has reached the current queue limit,

then the arriving customer is rejected. In this case, both the total number of rejections and the number of LP rejections are incremented.

If neither of the above two rejection conditions is met, the arriving customer is admitted. The number of customers in the system and in the queue are both incremented, along with their corresponding LP counts. The arrival time is recorded in the LP queue log. To maintain unified tracking, the system then refreshes the combined queue log by merging both priority records, ensuring HP entries appear first.

If there are no HP customers currently in the queue, the system sets the priority flag to indicate that LP customer is now at the head of the queue.

Finally, the system determines whether to initiate block generation:

* If the channel status is in ON state, and block generator is idle, and this customer is the only one in the queue, a new block generation event is scheduled based on an exponential random variable with rate .
* If more than one customer is in the queue, the block generation time remains unchanged.
* If the block generator is busy or the channel is OFF, the next block generation time is set to infinity to suspend the process.

### Block Generation Subprogram

As illustrated in Figure 4‑9, the block generation subprogram simulates the initiation of a block generation process. When this event is triggered, the simulation time is updated to the scheduled block generation time. Then, the area calculation function is invoked to update all time-averaged statistics based on the elapsed time since the last event. The next block generation time is set to infinity to prevent immediate retriggering, and the block generator status is marked as active.

To reserve sufficient space in the queue for block formation, the maximum queue size is reduced from to .

The system then determines the class of customers from which the block will be constructed, based on the current queue head status:

* **If the HP customer is at the head of the queue**:
  + If the number of HP customers exceeds the block size , exactly of them are moved into the block.
  + Otherwise, all HP customers are included in the block. If LP customers remain in the queue, the queue head status is updated accordingly; otherwise, it is cleared.
  + The block is marked as HP, and the consensus process is scheduled based on an exponential random variable with rate .
  + The total waiting time of HP customers in the block is calculated using their individual arrival times stored in the HP queue log, which is then updated by removing the corresponding entries, thereby reflecting their transition into the consensus stage.
* **If LP customer is at the head of the queue**:
  + If there are more than LP customers, exactly are selected for the block.
  + Otherwise, all remaining LP customers are included, and the queue is emptied.
  + The block is marked as LP, and the block departure event is scheduled based on an exponential random variable with rate .
  + The total waiting time of LP customers is calculated using their queue log, which is then updated accordingly.

After determining the block content, the system updates the overall waiting time in the queue for all customers, using the unified queue log. The combined queue log is then refreshed to reflect the current state of the customer queue.

Finally, the block log is updated with the entry time for each customer in the new block. This log is used for downstream statistics related to block-based consensus activity.

### Block Departure Subprogram

As illustrated in Figure 4‑10, the block departure subprogram simulates the completion of a block’s consensus process. When this event is triggered, the simulation time is updated to the current departure time. The area calculation function is then invoked to update all time-averaged statistics based on the elapsed time since the last event. The next block departure time is set to infinity to suspend further departure scheduling until a new block is formed.

The block generator status is reset to idle, and the customer queue capacity limit is restored to its original value , allowing the system to admit new arrivals without restriction.

The total waiting time of the block in the consensus stage is accumulated using the block log. The total number of customers currently in the system is decreased by the number of customers in the departing block, and the number of customers served is incremented accordingly. The block is then cleared.

The next processing depends on the priority class of the departing block:

* If it is a HP block, the corresponding class-specific consensus time is updated, and the number of HP customers in the system and served counters are adjusted.
* If it is a LP block, the LP statistics are updated in a similar manner.

After processing, the system clears the block log and resets the priority status of the block.

Finally, the system checks whether customers remain in the queue. If so, a new block generation event is scheduled based on the class of the customer at the head of the queue:

* If the HP customer is at the head of the queue, the next block generation is scheduled based on an exponential random variable with rate .
* If the LP customer is at the head of the queue, the event is scheduled with rate .

If the queue is empty, no block generation is scheduled, and the next block departure time is set to infinity.

### Switch Subprogram

As illustrated in Figure 4‑11, the switch subprogram simulates the transition of the system between ON and OFF operational states. When this event is triggered, the simulation time is updated to the current switch time. The area calculation function is then invoked to update all time-averaged statistics based on the elapsed time since the last event.

The system channel status is then toggled as follows:

* **If the system transitions from ON to OFF:**
  + The channel status is updated to OFF.
  + The next switch event is scheduled based on an exponential random variable with rate β (representing the OFF duration).
  + All pending block generation and block departure events are suspended by setting their scheduled times to infinity.
* **If the system transitions from OFF to ON:**
  + The channel status is updated to ON.
  + The next switch event is scheduled based on an exponential random variable with rate α (representing the ON duration).
  + If there is at least one customer in the queue and the block generator is idle:
    - A block generation event is scheduled based on an exponential random variable with rate or , depending on whether high- or LP customer is at the head of the queue.
  + If a block in consensus phase is suspended:
    - A block departure event is scheduled using the appropriate rate ( or ) based on the class of the current block.

Through this subprogram, the system emulates the effects of environmental disruptions such as connectivity loss or cyberattacks by alternating between active and inactive service periods. During the ON state, queuing, block generation and consensus operations proceed. During the OFF state, only customer arrivals are allowed, while block generation and consensus operation are temporarily halted.

### Flowchart Diagram



Figure ‑: Flow chart of main program

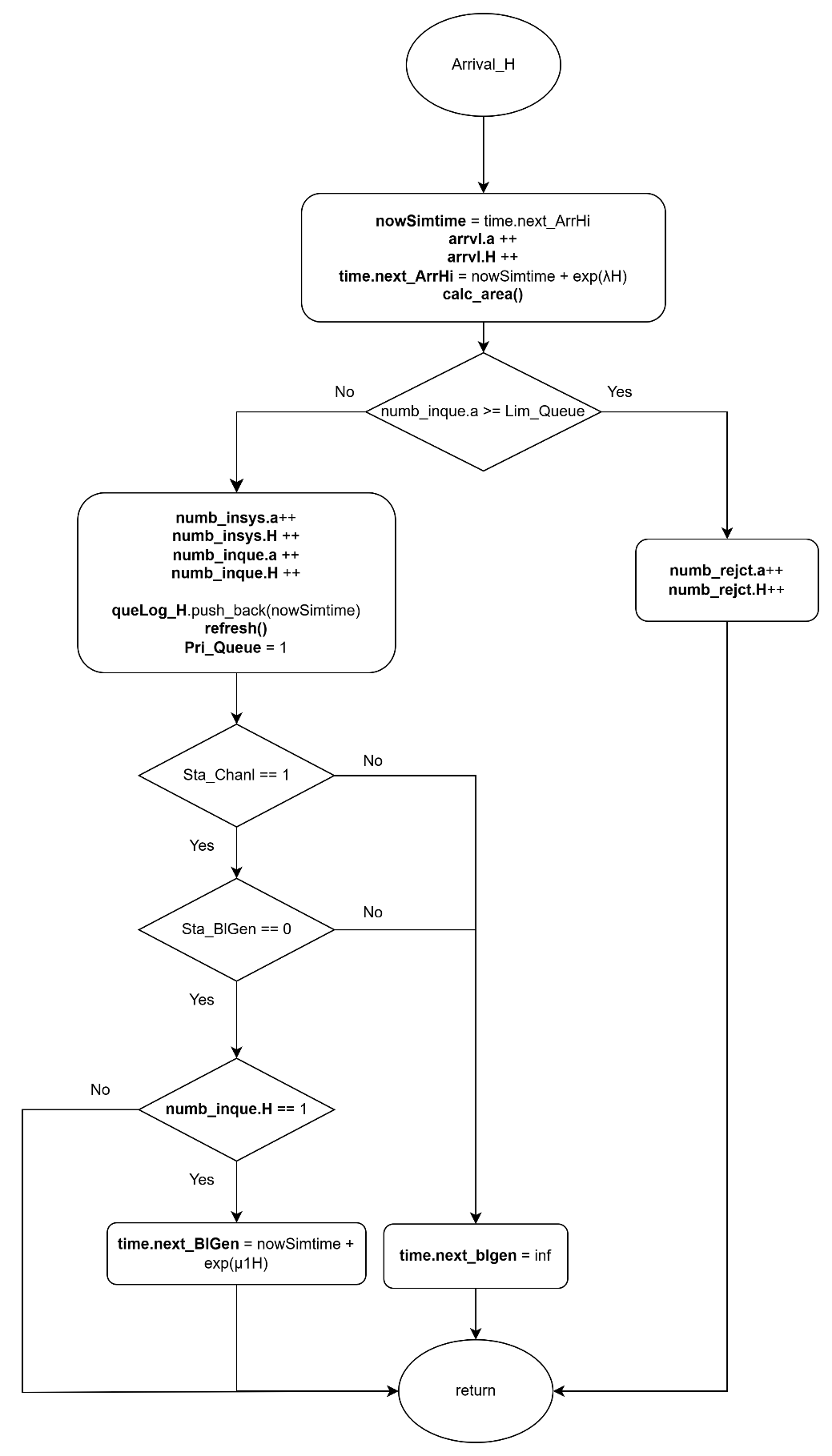


Figure ‑: Flow chart of HP arrival subprogram

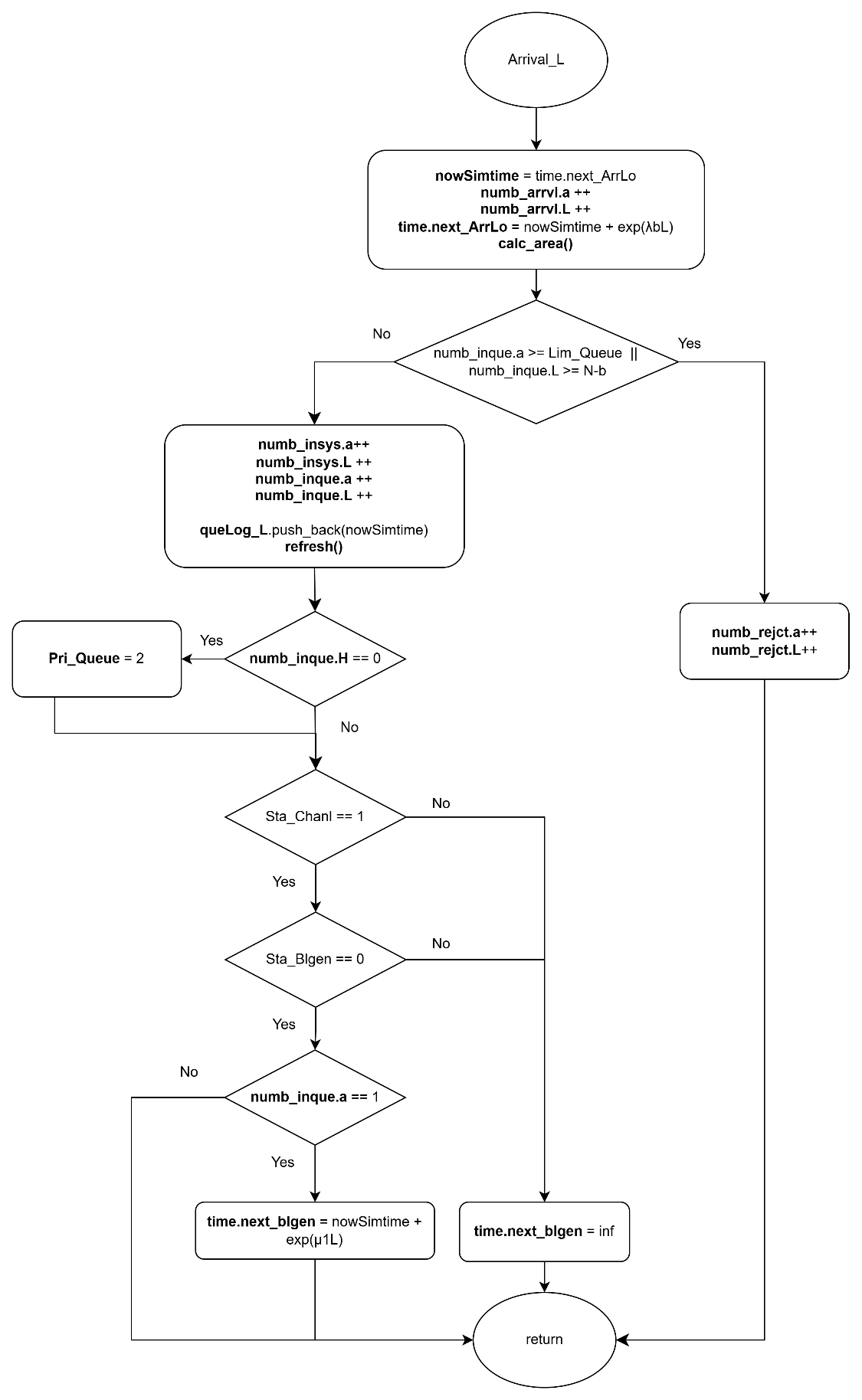


Figure ‑: Flow chart of LP arrival subprogram

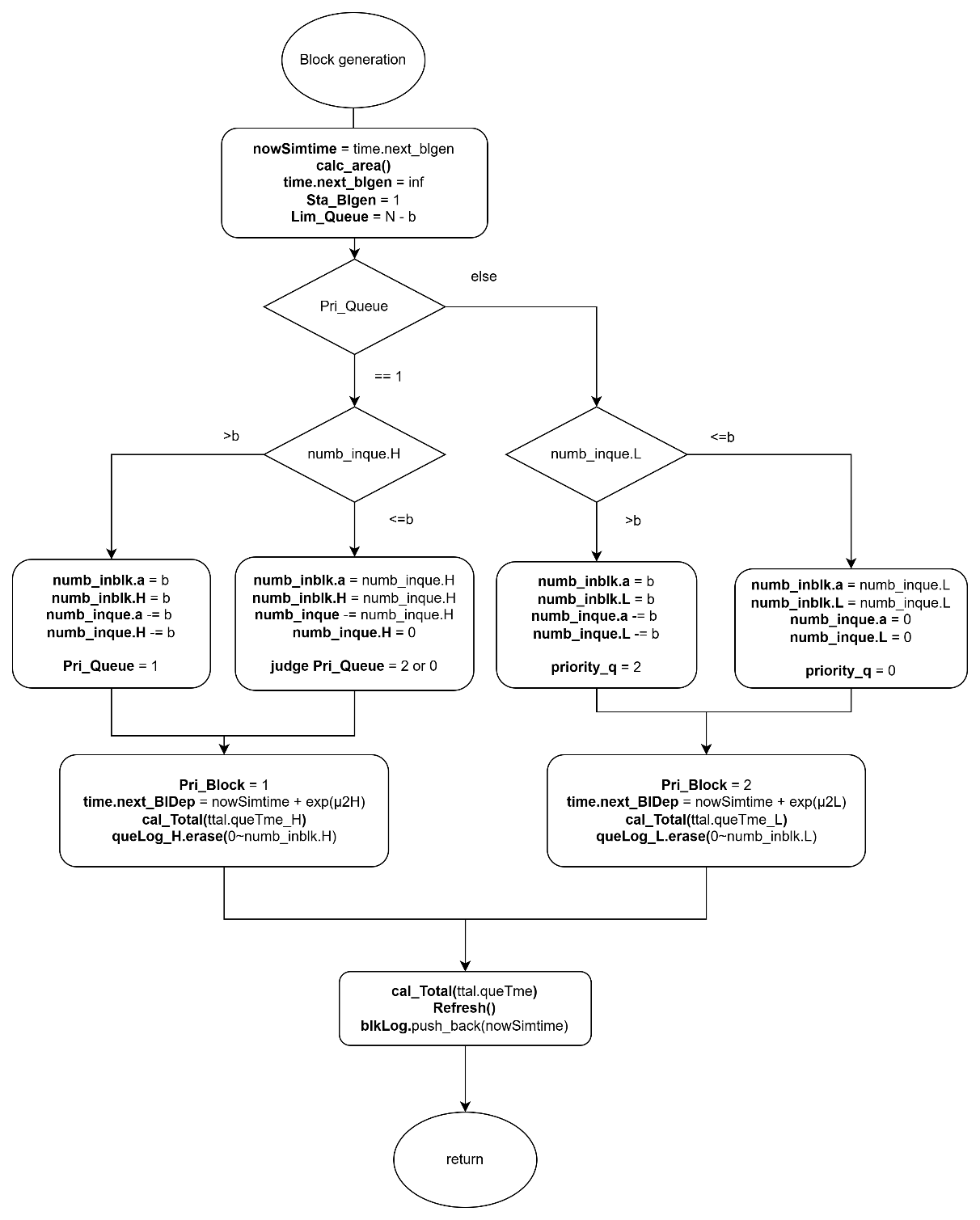


Figure ‑:Flow chart of block generation subprogram

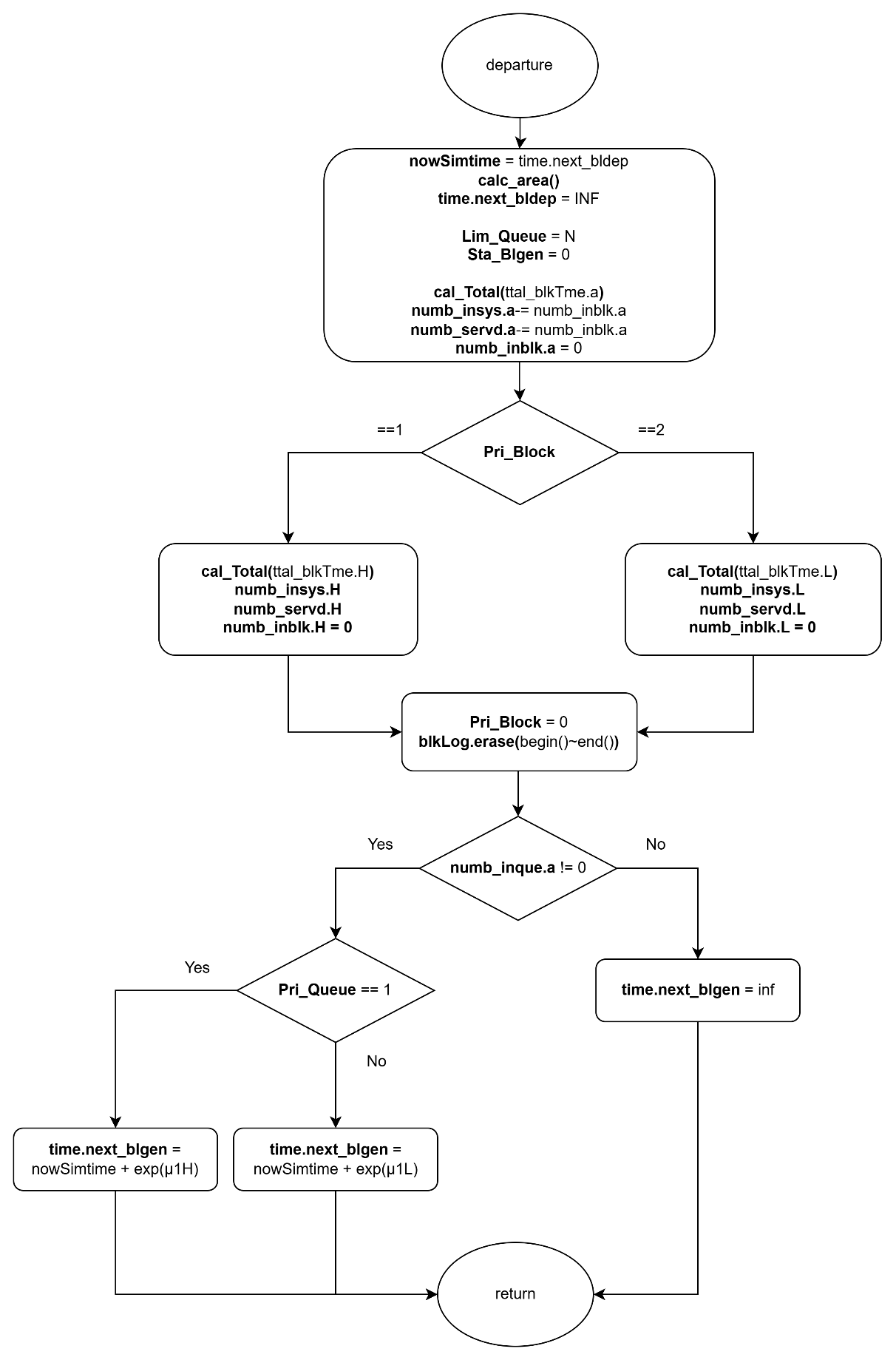


Figure ‑: Flow chart of block departure subprogram

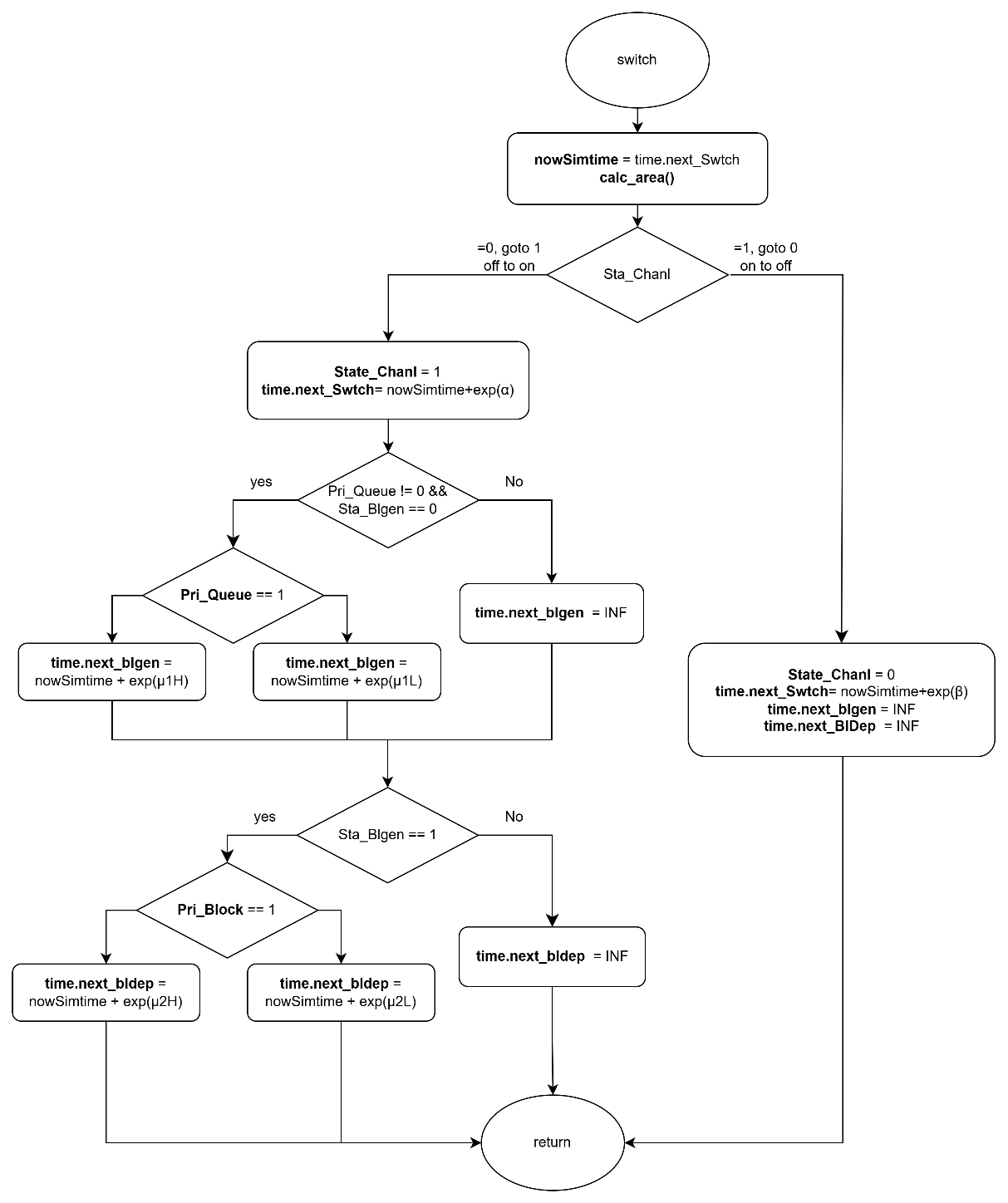


Figure ‑: Flow chart of switch subprogram

### Performance Index

First of all, the average number of HP and LP customers in the whole system, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑10) |
|  |  | (4‑11) |

The average number of customers in the whole system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑12) |

Second, the average number of HP and LP customers in customer queue, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑13) |
|  |  | (4‑14) |

The average number of customers in customer queue, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑15) |

Third, the average number of HP and LP customers in block queue, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑16) |
|  |  | (4‑17) |

The average number of customers in block queue, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑18) |

Fourth, the blocking probability of HP and LP customers in the system, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑19) |
|  |  | (4‑20) |

The blocking probability of the system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑21) |

Fifth, the throughput of HP and LP customers in the system, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑22) |
|  |  | (4‑23) |

The throughput of the system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑24) |

Sixth, the average waiting time of the HP and LP customers in the system, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑25) |
|  |  | (4‑26) |

The average waiting time in the system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑27) |

Seventh, the average waiting time of the HP and LP customers in the customer queue, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑28) |
|  |  | (4‑29) |

The average waiting time in the customer queue, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑30) |

Eighth, the average waiting time of the HP and LP customers in the block queue, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑31) |
|  |  | (4‑32) |

The average waiting time in the block queue, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑33) |

Finally, the average number of HP and LP blocks participating in the consensus process per unit of time, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑34) |
|  |  | (4‑35) |

The average number of blocks participating in the consensus process per unit of time within a block, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑36) |

## Scenario 3: Single-Class Customer with Impatience

In this simulation model, we consider a blockchain system that handles a single class of customers, where customers arrive according to a Poisson process and are served under the First-Come-First-Served (FCFS) discipline.

The system consists of two queues: the customer queue, where customers wait for block generation, and the block queue, where customers participate in the consensus process after being grouped into a block. Block generation follows a partial batch service policy, allowing 1 to customers to form a block. Once a block is formed, it is transferred to the block queue. Upon completion of the consensus process, all customers in the block exit the system.

During the OFF state, caused by interruptions such as attacks or connectivity issues, both block generation and consensus processes are suspended, although new customers may still arrive and be admitted. During the ON state, all services resume normally. To preserve system integrity, a constraint is imposed on the maximum number of customers allowed in the customer queue: when the block queue is empty, up to customers may wait; otherwise, the limit is reduced to .

In this scenario, customers may abandon the system if they wait in the queue for too long without being served. Upon entering the customer queue, each customer is assigned a personal impatience threshold based on an exponential random variable with rate . If this threshold expires before the customer is grouped into a block, the customer abandons the queue and is removed from the system.

This scenario captures the impact of impatience-driven abandonment on system performance. It allows us to evaluate additional metrics such as impatience probability and its effect on throughput, queue occupancy, and overall system responsiveness under variable service delays and transient interruptions.

### Main program

The main program executes a series of steps to simulate the blockchain queuing system with customer impatience, as illustrated in Figure 4‑12. At the beginning of each simulation run, all relevant variables are initialized. This includes resetting statistical parameters, setting the next block generation time and next departure time to infinity, marking the channel status as ON, initializing the block generation status as idle, and setting the customer queue limit to .

Next, the system parameters are configured. These include the maximum customer queue capacity (), the maximum number of customers per block (), the arrival rate (), the block generation rate (), the consensus rate (), the impatience rate (), and the ON/OFF switching rates ( and ) for the system channel.

The program generates the next arrival time and channel switch time using exponential random variables based on the corresponding system parameters. Impatience threshold will be dynamically scheduled when customers enter the queue, rather than at initialization. During the simulation, it compares the scheduled times of five events and selects the earliest event to execute its corresponding subprogram.

Finally, a while loop is used to repeat the simulation until a predefined number of customer arrivals has been reached. Once this condition is met, the simulation terminates and the performance statistics are output.

### Arrival Subprogram

Figure 4‑13 illustrated the flow chart of the arrival subprogram, simulates the arrival of a new customer to the system. Upon invocation, the total number of arrivals is incremented, and the simulation time is updated to the scheduled arrival time. The time for the next arrival is then scheduled using an exponential interarrival time generated with the arrival rate . Then, the area calculation function is invoked to update all time-averaged statistics based on the elapsed time since the last event.

Next, the system checks whether the customer queue has reached its capacity limit.

* If the queue is full, the arriving customer is rejected, and the number of rejections is incremented.
* If the queue is not full, the customer is admitted to the queue. In this case, the number of customers in the system and in the queue are incremented. The customer's arrival time and corresponding impatience threshold are recorded as a pair in the queue log. The impatience threshold is generated based on an exponential random variable with rate , and represents the maximum amount of time the customer is willing to wait before abandoning the system.

The system determines whether to initiate block generation:

* If the channel status is in ON state, and block generator is idle, and this customer is the only one in the queue, a new block generation event is scheduled based on an exponential random variable with rate .
* If the block generator is busy or the channel is OFF, the next block generation time is set to infinity to suspend the process.

Finally, the impatience tracker is updated by identifying the customer with the earliest threshold in the queue. The next impatience event is scheduled to occur at this earliest threshold point.

### Block Generation Subprogram

Figure 4‑14 illustrates the flow chart of the block generation subprogram, which simulates the initiation of a block generation process. When this event is triggered, the simulation time is updated to the scheduled block generation time. Then, the area calculation function is invoked to update all time-averaged statistics based on the elapsed time since the last event.

Next, the block generator status is set to busy, indicating that a block is currently being generated. To ensure sufficient space for the upcoming consensus process, the capacity limit of the customer queue is reduced from to , where is the maximum number of customers allowed in a block.

The system then determines how many customers should be transferred from the queue into the block:

* If more than customers are waiting in the queue, exactly are selected.
* Otherwise, all remaining customers in the queue are moved into the block.

The number of customers transferred into the block is recorded, and the queue size is adjusted accordingly. A block departure event is then scheduled based on an exponential random variable with rate . After this, the next block generation time is set to infinity to prevent immediate retriggering.

For each customer that enters the block, their corresponding arrival time is logged into the block log. These timestamps are subsequently used to compute the cumulative queueing time. This calculation is performed using the total waiting time function, which sums the time differences between the current simulation time and each customer's original queue entry time.

Finally, the corresponding entries in the queue log are removed to reflect that these customers have exited the queue and are now participating in the consensus process. The system then updates the impatience tracker by identifying the next customer with the earliest remaining impatience threshold. The next impatience event is scheduled accordingly.

### Block Departure Subprogram

Figure 4‑15 illustrates the flow chart of the departure subprogram, which simulates the completion of a block consensus process. When this event is triggered, the simulation time is updated to the scheduled block departure time. Then, the area calculation function is invoked to update all time-averaged statistics based on the elapsed time since the last event.

At this point, the block generation status is reset to idle, and the customer queue capacity limit is restored to its original value , allowing the queue to accept new customers at full capacity. The block departure event is considered completed and is therefore cleared.

The program then calculates the total time that the current block of customers spent in the consensus stage. This is achieved using the block time accumulation function, which computes the total time difference between the current simulation time and each customer's recorded entry into the block.

After consensus completion, the number of customers currently in the system is decreased by the number of customers in the departing block, and the total number of customers served is incremented accordingly. The block is now empty, and all associated entries in the block log are removed.

Finally, if there are still customers waiting in the queue, a new block generation event is scheduled based on an exponential random variable with rate .

### Switch Subprogram

Figure 4‑16 illustrates the flow chart of the switch subprogram, which simulates the transition of the system between ON and OFF states. When this event is triggered, the simulation time is updated to the scheduled switch time. Then, the area calculation function is invoked to update all time-averaged statistics based on the elapsed time since the last event.

The system channel status is then toggled as follows:

* **If the system transitions from ON to OFF:**
  + The channel status is set to OFF.
  + The next switch event is scheduled based on an exponential random variable with rate (representing the OFF duration).
  + All ongoing service operations are suspended by setting both the block generation and block departure event times to infinity.
* **If the system transitions from OFF to ON:**
  + The channel status is set to ON.
  + The next switch event is scheduled based on an exponential random variable with rate (representing the ON duration).
  + If there is at least one customer in the queue and the block generator is currently idle:
    - A block generation event is scheduled based on an exponential random variable with rate .
  + If a block in consensus phase is suspended:
    - A block departure event is scheduled using an exponential random variable with rate .

Through this subprogram, the simulation captures the stochastic availability of the system by alternating between operational and suspended phases, reflecting real-world unreliability such as downtime or external disruptions. During the ON period, block generation and consensus operations proceed as normal. During the OFF period, these processes are temporarily halted while new customer arrivals may still occur.

### Impatience subprogram

Figure 4‑17 illustrates the flow chart of the impatience subprogram, which simulates the event in which a customer abandons the system after exceeding their impatience threshold. When this event is triggered, the simulation time is updated to the scheduled impatience threshold. The area calculation function is then invoked to update all time-averaged statistics based on the elapsed time since the last event.

The customer whose impatience threshold has expired is removed from the queue and from the system. Accordingly, the number of customers in the system and in the queue are both decremented, and the total number of impatient departures is incremented.

The actual waiting time of the abandoning customer is calculated as the difference between their impatience threshold and their recorded arrival time. This value is accumulated as part of the total impatient time, which is used to compute impatience-related performance metrics.

The customer’s entry is then removed from the queue log to reflect their departure. Following this update, the system searches for the next earliest impatience threshold among the remaining customers in the queue. The impatience tracker is updated, and the next impatience event is scheduled accordingly.

### Flowchart Diagram



Figure ‑: Flow chart of main program

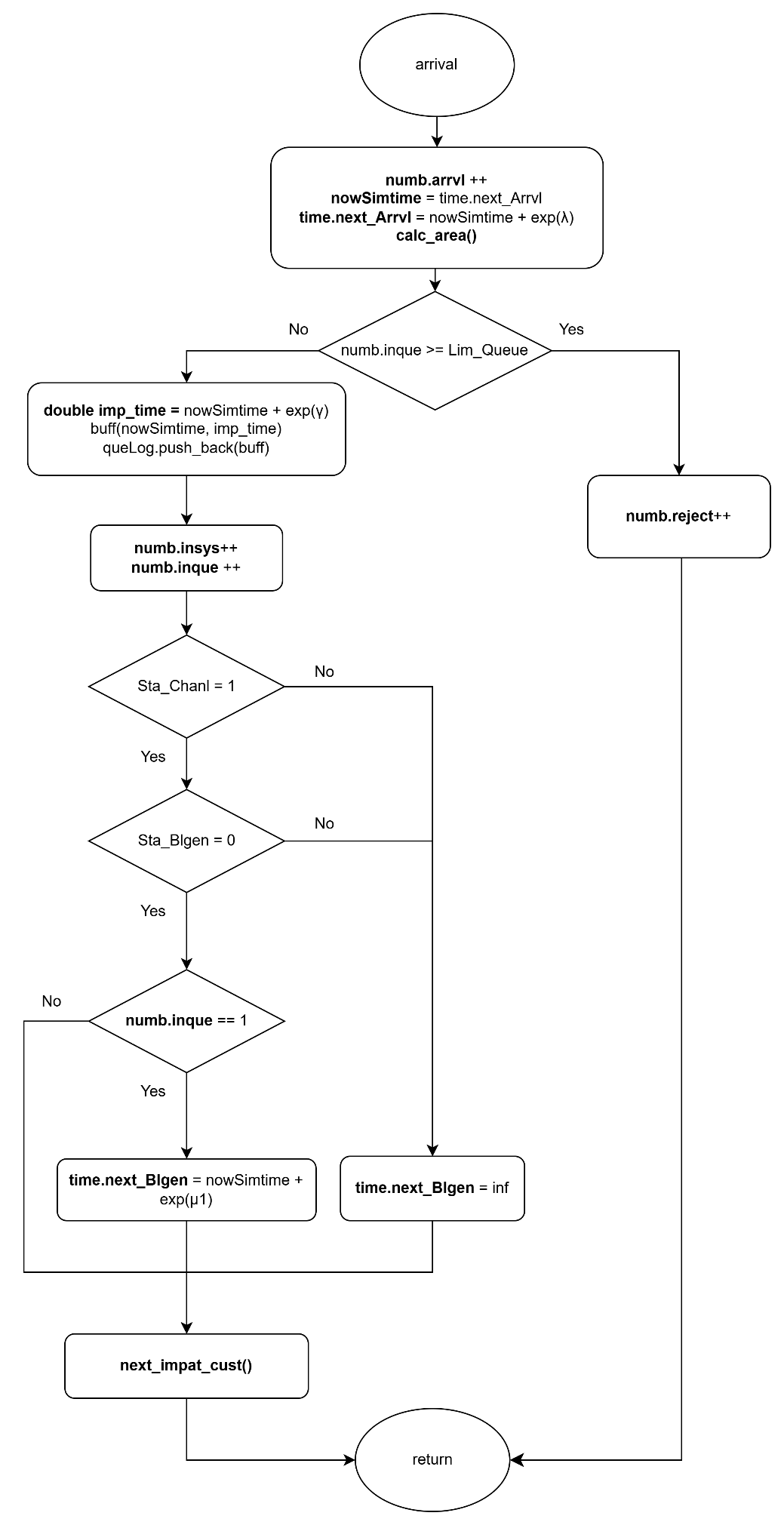


Figure ‑: Flow chart of arrival subprogram

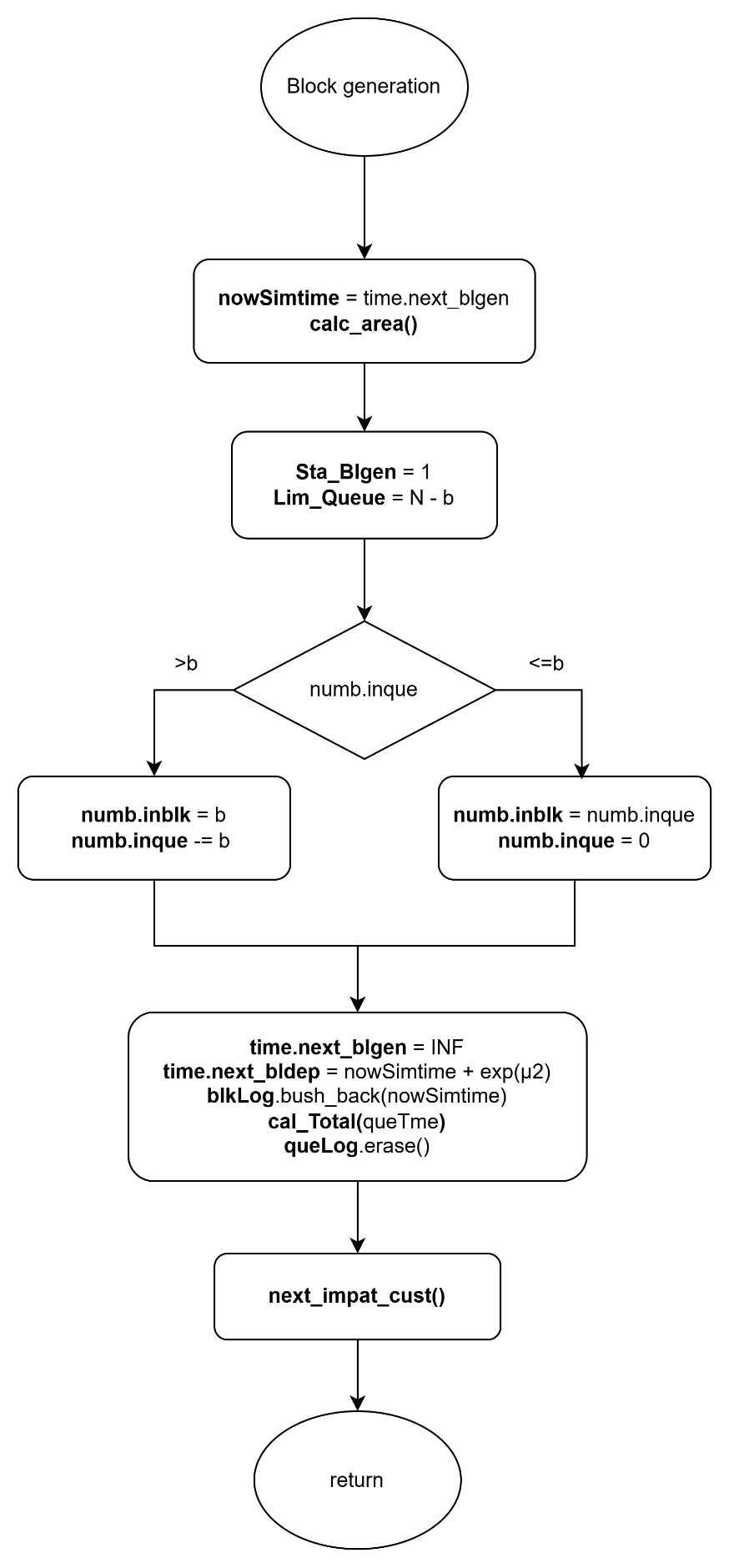


Figure ‑:Flow chart of block generation subprogram

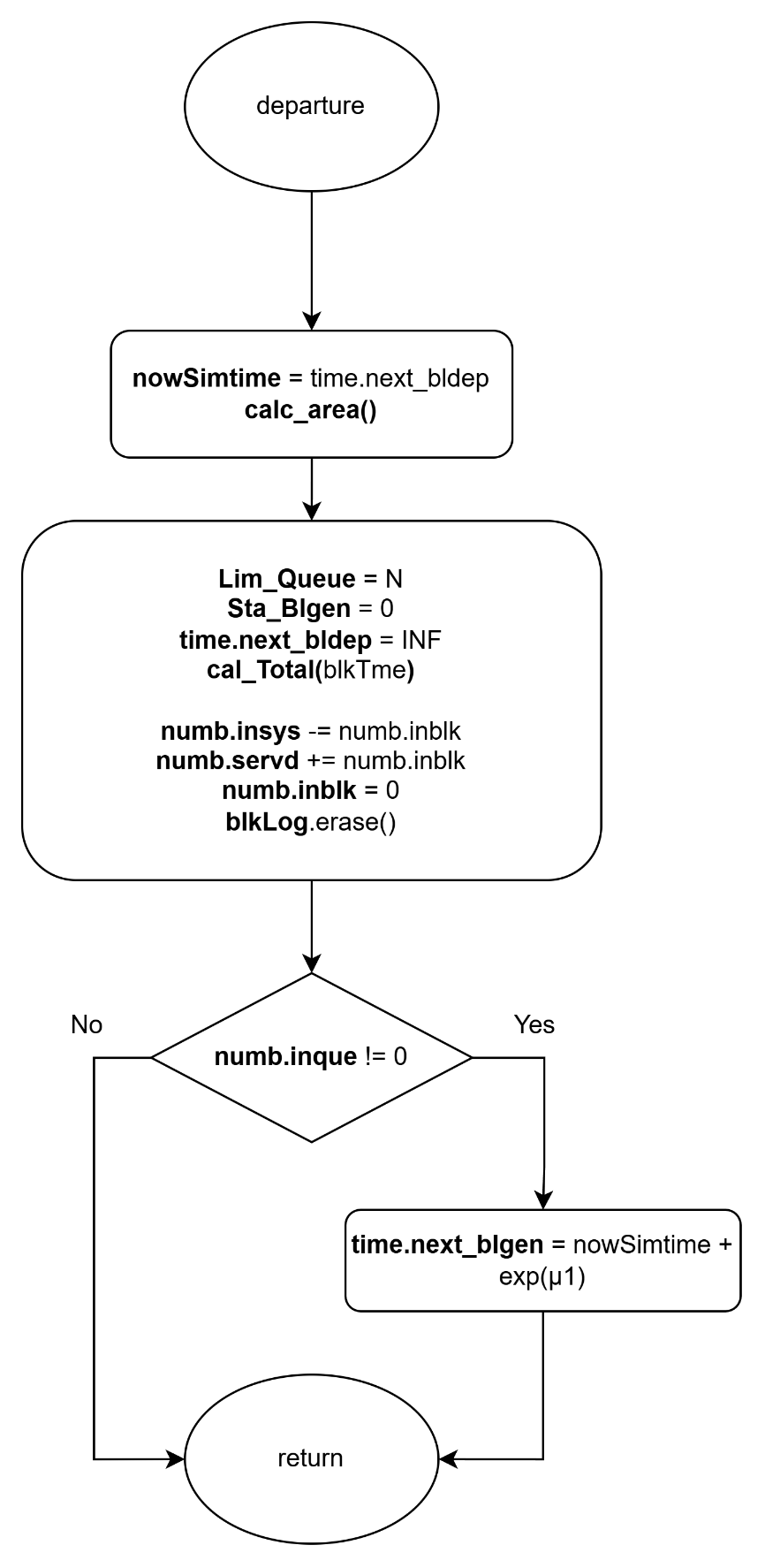


Figure ‑: Flow chart of block departure subprogram

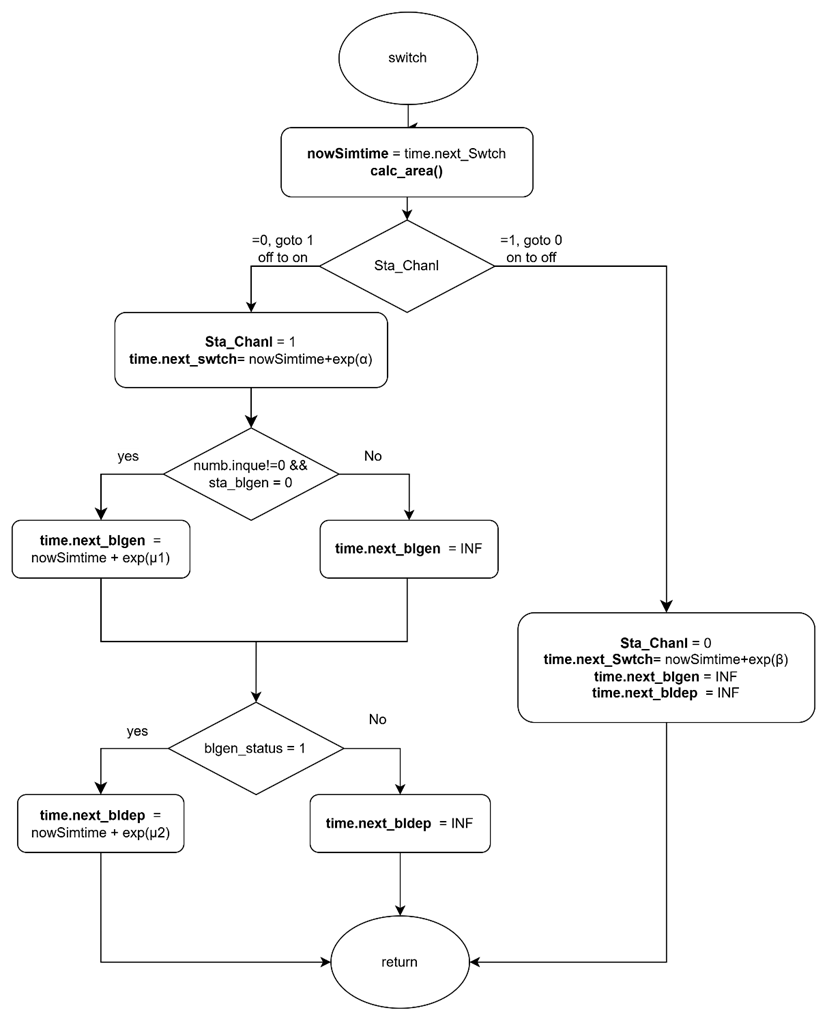


Figure ‑: Flow chart of switch subprogram



Figure ‑: Flow chart of impatience subprogram

### Performance Index

First of all, the average number of customers in the whole system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑37) |

Second, the average number of customers in customer queue, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑38) |

Third, the average number of customers in block queue, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑39) |

Fourth, the blocking probability of the system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑40) |

Fifth, the impatient probability of the system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑41) |

Sixth, the throughput of the system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑42) |

Seventh, the average waiting time in the customer queue, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑43) |

Eighth, the average waiting time in the block queue, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑44) |

Ninth, the average waiting time in the system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑45) |

Finally, the average number of blocks participating in the consensus process per unit of time, denoted by , is given below.

|  |  |  |
| --- | --- | --- |
|  |  | (4‑46) |

## Scenario 4: Two-Class Customer with Impatience

In this simulation model, we consider a blockchain system that handles two classes of customers: HP and LP customers. Customers of different priorities arrive according to an independent Poisson process, and customers of the same priority are served under the First-Come-First-Served (FCFS) discipline. Customers of different priorities are handled using a non-preemptive priority rule, where HP customers are always placed ahead of LP customers in the queue, but ongoing service for a LP block cannot be interrupted once initiated.

The system consists of two queues: the customer queue and the block queue. HP and LP customers both enter the customer queue upon arrival if possible. Block generation follows a partial batch service policy and operates on customers of only one priority class at a time. Each block can include at most customers. Once a block that is composed solely of HP or LP customer(s) is formed, it is transferred to the block queue. After completing the consensus process, all customers in the block exit the system.

The system alternates between ON and OFF periods to reflect external interruptions such as cyberattacks or connection failures. During the OFF state, both block generation and consensus process are suspended, though new customers may still arrive and be queued. During the ON state, all services resume as normal.

To preserve system integrity and fairness, different queue capacity constraints apply based on customer class and system state. For HP customers, the maximum number allowed in the customer queue is when the block queue is empty, and when it is occupied. For LP customers, the customer queue capacity is always limited to , regardless of the block queue state.

In this scenario, customers may abandon the system if they wait in the queue too long without being served. Upon entering the customer queue, each of HP and LP customers are assigned a personal impatience threshold based on an exponential random variable with rate and , respectively. If this threshold expires before the customer is grouped into a block, the customer abandons the queue and is removed from the system.

This scenario is designed to study the combined effects of non-preemptive priority scheduling and customer impatience. It enables performance evaluation in terms of class-specific metrics such as throughput, queue length, waiting time, blocking probability, and impatience probability under dynamic and congested conditions.

### Main program

The main program executes a series of steps to simulate the blockchain queuing system with two classes of customers, as illustrated in Figure 4‑18. At the beginning of each simulation run, all relevant variables are initialized. This includes resetting statistical parameters, setting the next block generation time and next departure time to infinity, marking the channel status as ON, initializing the block generation status as idle, and setting the customer queue limit to .

Next, the system parameters are configured. These include the maximum customer queue capacity (), the maximum number of customers per block (), the arrival rates for HP and LP customers ( and ), the block generation rates ( and ), the consensus rates ( and ) , the impatience rates ( and ), and the ON/OFF switching rates ( and ) for the system channel.

The program then generates the next arrival times for both HP and LP customers, as well as the channel switch time, using exponential random variables based on the corresponding system parameters. During the simulation, it compares the scheduled times of five events and selects the earliest event to execute its corresponding subprogram.

Finally, a while loop is used to repeat the simulation until a predefined number of customer arrivals has been reached. Once this condition is met, the simulation terminates and the performance statistics are output.

### High-Priority Arrival Subprogram

As illustrated in Figure 4‑19, the HP arrival subprogram simulates the arrival of a HP customer to the system. When this event is triggered, the simulation time is updated to the current arrival time. The arrival counters are incremented to reflect both the total number of customers and the number of HP arrivals. The next arrival event for HP customers is then scheduled based on an exponential random variable with rate . Then, the area calculation function is invoked to update all time-averaged statistics based on the elapsed time since the last event.

Next, the system checks whether the customer queue has reached its capacity limit.

* If the queue is full, the arriving customer is rejected. In this case, both the total number of rejections and the number of HP rejections are incremented.
* If the queue is not full, the arriving customer is admitted. The number of customers in the system and in the queue are both incremented, along with their corresponding HP counts. The customer's arrival time and corresponding impatience threshold are recorded as a pair in the queue log. The impatience threshold is generated based on an exponential random variable with rate , and represents the maximum amount of time the customer is willing to wait before abandoning the system.

Then, the system updates the unified queue log by merging the HP and LP arrival records, ensuring that HP entries appear first. The system then sets the priority flag to indicate that HP customers are currently at the head of the queue.

The system determines whether to initiate block generation:

* If the channel status is in ON state, and block generator is idle, and this customer is the only one in the queue, a new block generation event is scheduled based on an exponential random variable with rate .
* If the block generator is busy or the channel is OFF, the next block generation time is set to infinity to suspend the process.

Finally, the impatience tracker is updated by identifying the customer with the earliest threshold in the queue. The next impatience event is scheduled to occur at this earliest threshold point.

### Low-Priority Arrival Subprogram

As illustrated in Figure 4‑20, the LP subprogram simulates the arrival of a LP customer to the system. When this event is triggered, the simulation time is updated to the scheduled arrival time. The arrival counters are incremented to reflect both the total number of customers and the number of LP arrivals.

The next arrival event for LP customers is then scheduled based on an exponential random value with the rate . Then, the area calculation function is invoked to update all time-averaged statistics based on the elapsed time since the last event.

Next, the system checks whether the customer queue has reached its capacity limit. The rejection condition depends on the system’s block generation state:

* If the number of LP customers in the queue has reached , or
* The total number of customers in the queue has reached the current queue limit,

then the arriving customer is rejected. In this case, both the total number of rejections and the number of LP rejections are incremented.

If neither of the above two rejection conditions is met, the arriving customer is admitted. The number of customers in the system and in the queue are both incremented, along with their corresponding LP counts. The customer’s arrival time and corresponding impatience threshold are recorded as a pair in the LP queue log. The impatience threshold is generated based on an exponential random variable with rate , and represents the maximum amount od time the customer is willing to wait before abandoning the system.

To maintain unified tracking, the system then refreshes the combined queue log by merging both priority records, ensuring HP entries appear first. If there are no HP customers currently in the queue, the system sets the priority flag to indicate that LP customer is now at the head of the queue.

Finally, the system determines whether to initiate block generation:

* If the channel status is in ON state, and block generator is idle, and this customer is the only one in the queue, a new block generation event is scheduled based on an exponential random variable with rate .
* If the block generator is busy or the channel is OFF, the next block generation time is set to infinity to suspend the process.

Finally, the impatience tracker is updated by identifying the customer with the earliest threshold in the queue. The next impatience event is scheduled to occur at this earliest threshold point.

### Block Generation Subprogram

As illustrated in Figure 4‑21, the block generation subprogram simulates the initiation of a block generation process. When this event is triggered, the simulation time is updated to the scheduled block generation time. Then, the area calculation function is invoked to update all time-averaged statistics based on the elapsed time since the last event. The next block generation time is set to infinity to prevent immediate retriggering, and the block generator status is marked as active.

To reserve sufficient space in the queue for block formation, the maximum queue size is reduced from to .

The system then determines the class of customers from which the block will be constructed, based on the current queue head status:

* **If the HP customer is at the head of the queue**:
  + If the number of HP customers exceeds the block size , exactly of them are moved into the block.
  + Otherwise, all HP customers are included in the block. If LP customers remain in the queue, the queue head status is updated accordingly; otherwise, it is cleared.
  + The block is marked as HP, and the consensus process is scheduled based on an exponential random variable with rate .
  + The total waiting time of HP customers in the block is calculated using their individual arrival times stored in the HP queue log, which is then updated by removing the corresponding entries, thereby reflecting their transition into the consensus stage.
* **If LP customer is at the head of the queue**:
  + If there are more than LP customers, exactly are selected for the block.
  + Otherwise, all remaining LP customers are included, and the queue is emptied.
  + The block is marked as LP, and the block departure event is scheduled based on an exponential random variable with rate .
  + The total waiting time of LP customers is calculated using their queue log, which is then updated accordingly.

After the block is formed, the system updates the overall waiting time in the queue for all customers, using the unified queue log. The combined queue log is then refreshed to reflect the current state of the customer queue.

Next, the block log is updated with the entry time for each customer in the new block. This log is used for downstream statistics related to block-based consensus activity.

Finally, the impatience tracker is updated by identifying the customer with the earliest threshold in the queue. The next impatience event is scheduled to occur at this earliest threshold point.

### Block Departure Subprogram

As illustrated in Figure 4‑22, the block departure subprogram simulates the completion of a block’s consensus process. When this event is triggered, the simulation time is updated to the current departure time. The area calculation function is then invoked to update all time-averaged statistics based on the elapsed time since the last event. The next block departure time is set to infinity to suspend further departure scheduling until a new block is formed.

The block generator status is reset to idle, and the customer queue capacity limit is restored to its original value , allowing the system to admit new arrivals without restriction.

The total waiting time of the block in the consensus stage is accumulated using the block log. The total number of customers currently in the system is decreased by the number of customers in the departing block, and the number of customers served is incremented accordingly. The block is then cleared.

The next processing depends on the priority class of the departing block:

* If it is a HP block, the corresponding class-specific consensus time is updated, and the number of HP customers in the system and served counters are adjusted.
* If it is a LP block, the LP statistics are updated in a similar manner.

After processing, the system clears the block log and resets the priority status of the block.

Finally, the system checks whether customers remain in the queue. If so, a new block generation event is scheduled based on the class of the customer at the head of the queue:

* If the HP customer is at the head of the queue, the next block generation is scheduled based on an exponential random variable with rate .
* If the LP customer is at the head of the queue, the event is scheduled with rate .

If the queue is empty, no block generation is scheduled, and the next block departure time is set to infinity.

### Switch Subprogram

As illustrated in Figure 4‑23, the switch subprogram simulates the transition of the system between ON and OFF operational states. When this event is triggered, the simulation time is updated to the current switch time. The area calculation function is then invoked to update all time-averaged statistics based on the elapsed time since the last event.

The system channel status is then toggled as follows:

* **If the system transitions from ON to OFF:**
  + The channel status is updated to OFF.
  + The next switch event is scheduled based on an exponential random variable with rate β (representing the OFF duration).
  + All pending block generation and block departure events are suspended by setting their scheduled times to infinity.
* **If the system transitions from OFF to ON:**
  + The channel status is updated to ON.
  + The next switch event is scheduled based on an exponential random variable with rate α (representing the ON duration).
  + If there is at least one customer in the queue and the block generator is idle:
    - A block generation event is scheduled based on an exponential random variable with rate or , depending on whether the high- or LP customer is at the head of the queue.
  + If a block in consensus phase is suspended:
    - A block departure event is scheduled using the appropriate rate ( or ) based on the class of the current block.

Through this subprogram, the system emulates the effects of environmental disruptions such as connectivity loss or cyberattacks by alternating between active and inactive service periods. During the ON state, queuing, block generation and consensus operations proceed. During the OFF state, only customer arrivals are allowed, while block generation and consensus operation are temporarily halted.

### Impatience subprogram

Figure 4‑24 illustrates the flow chart of the impatience subprogram, which simulates the event in which a customer abandons the system after exceeding their impatience threshold. When this event is triggered, the simulation time is updated to the scheduled impatience threshold. The area calculation function is then invoked to update all time-averaged statistics based on the elapsed time since the last event.

The customer whose impatience threshold has expired is removed from the queue and from the system. Depending on the customer’s priority class, the number of customer in the system and in the queue are both decremented, and the total number of impatient departures is incremented for both the system and the corresponding class.

The actual waiting time of the abandoning customer is calculated as the difference between their impatience threshold and their recorded arrival time. This value is accumulated as part of the total impatient time, which is used to compute impatience-related performance metrics.

The customer’s entry is then removed from the corresponding priority queue log to reflect their departure. The unified queue log is refreshed to reflect the current state of the system.

After this update, the system checks the remaining customers in the queue. If the queue is empty, the next block generation time is set to infinity, and the priority flag is cleared. If at least one customer remains, the system sets the queue head priority to high if at least one HP customer is still waiting; otherwise, it sets it to low.

Finally, the impatience tracker is updated by identifying the customer with the earliest threshold in the queue. The next impatience event is scheduled to occur at this earliest threshold point.

### Flowchart Diagram



Figure ‑: Flow chart of main program

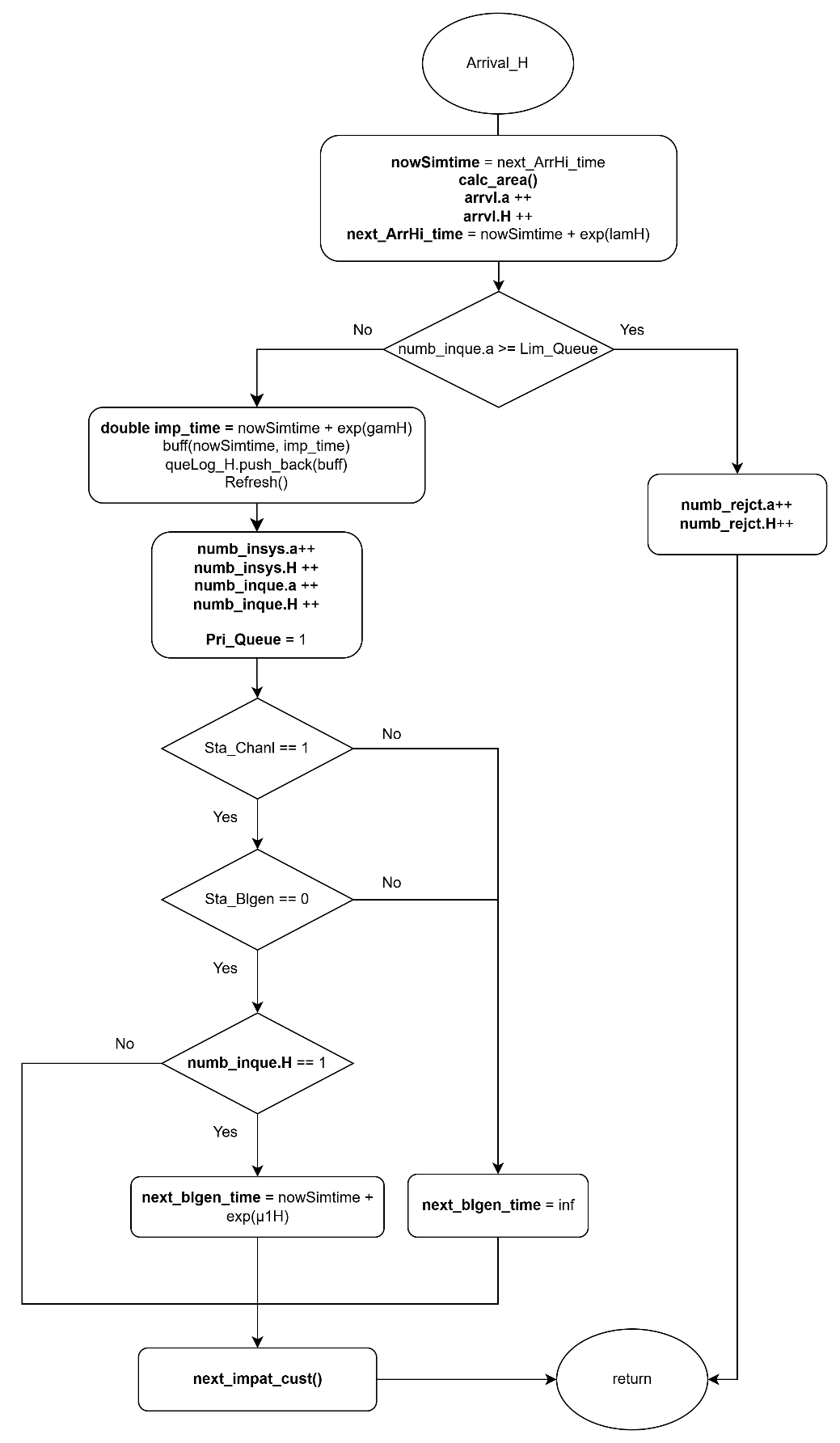


Figure ‑: Flow chart of HP arrival subprogram

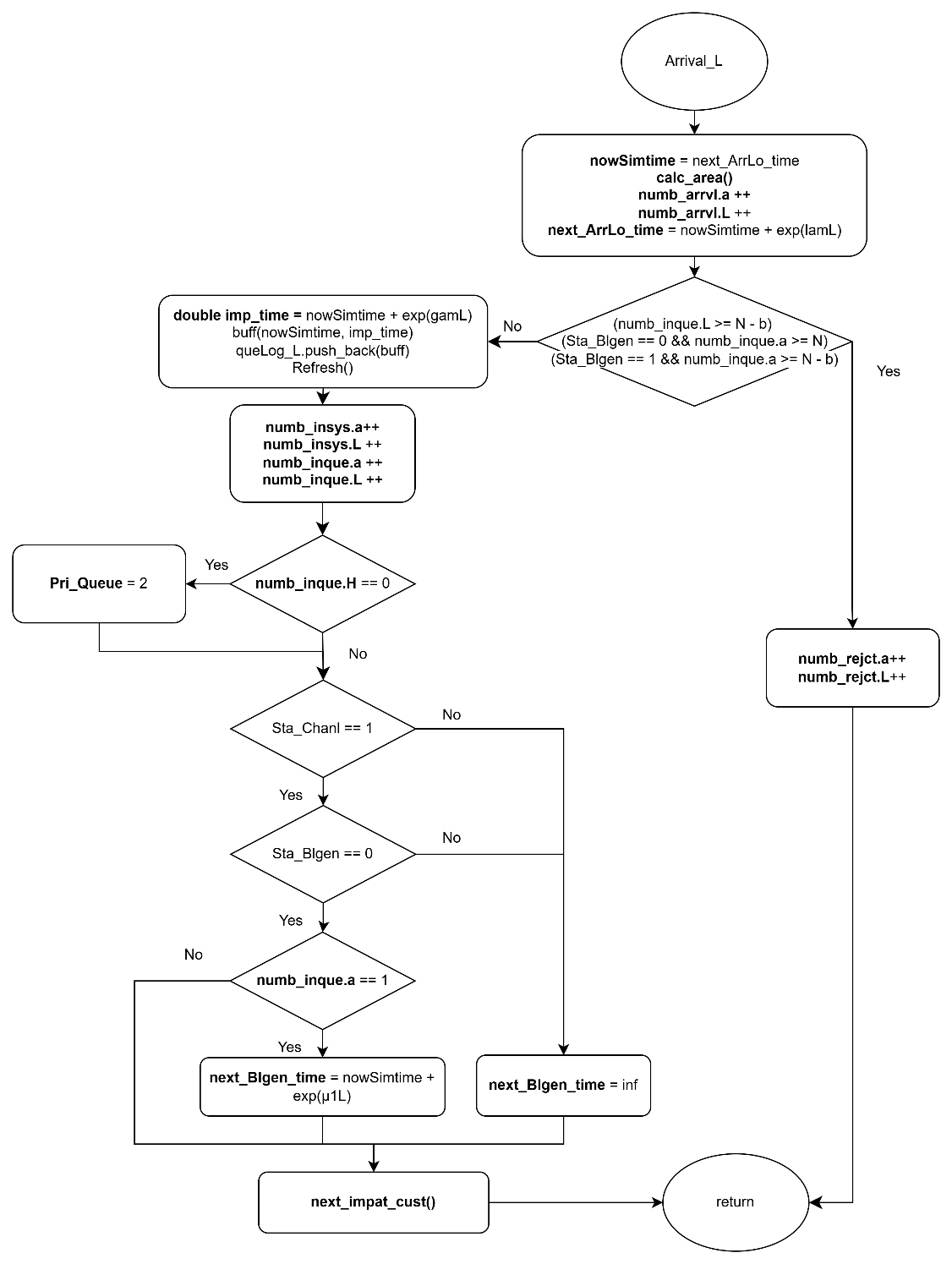


Figure ‑: Flow chart of LP arrival subprogram

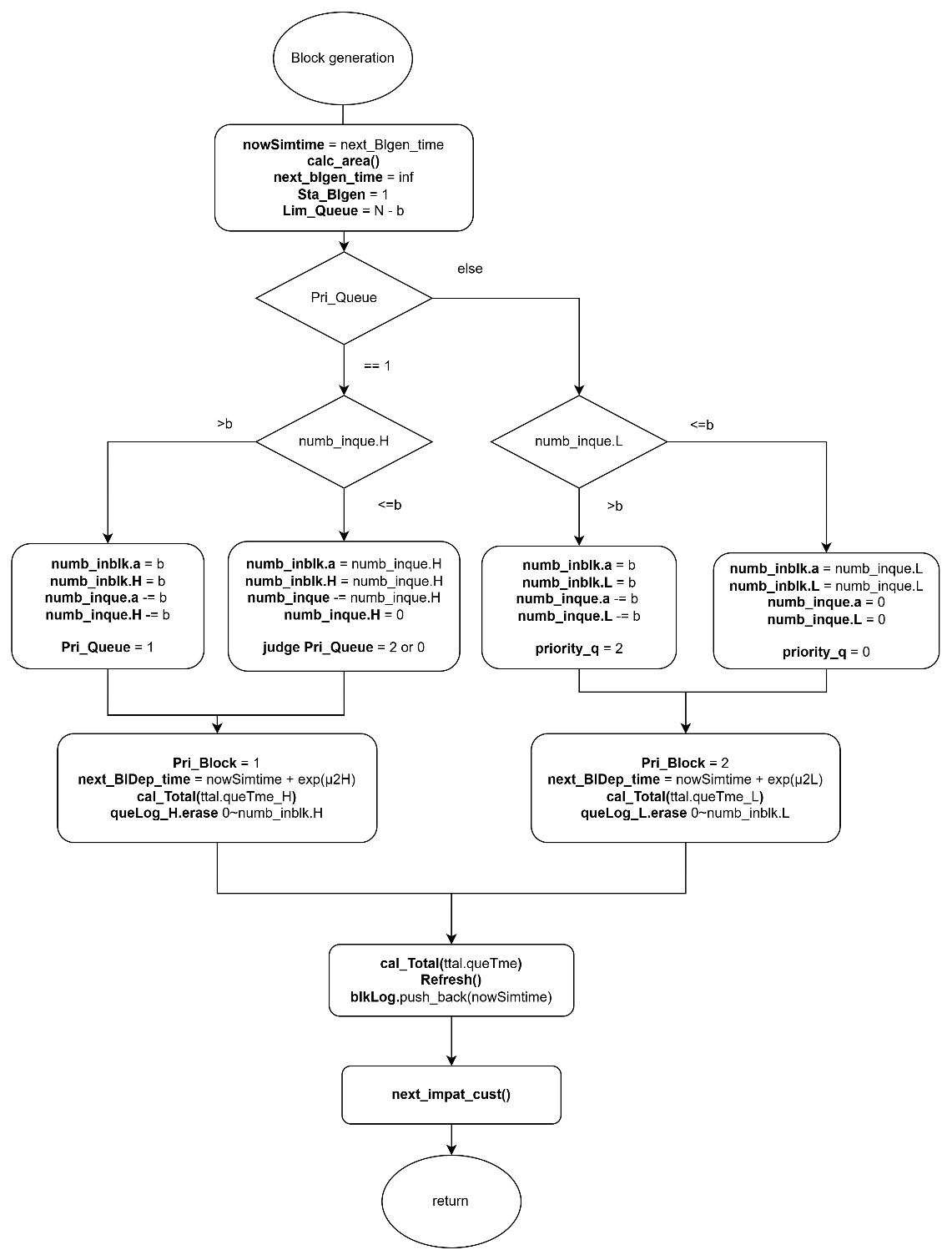


Figure ‑:Flow chart of block generation subprogram

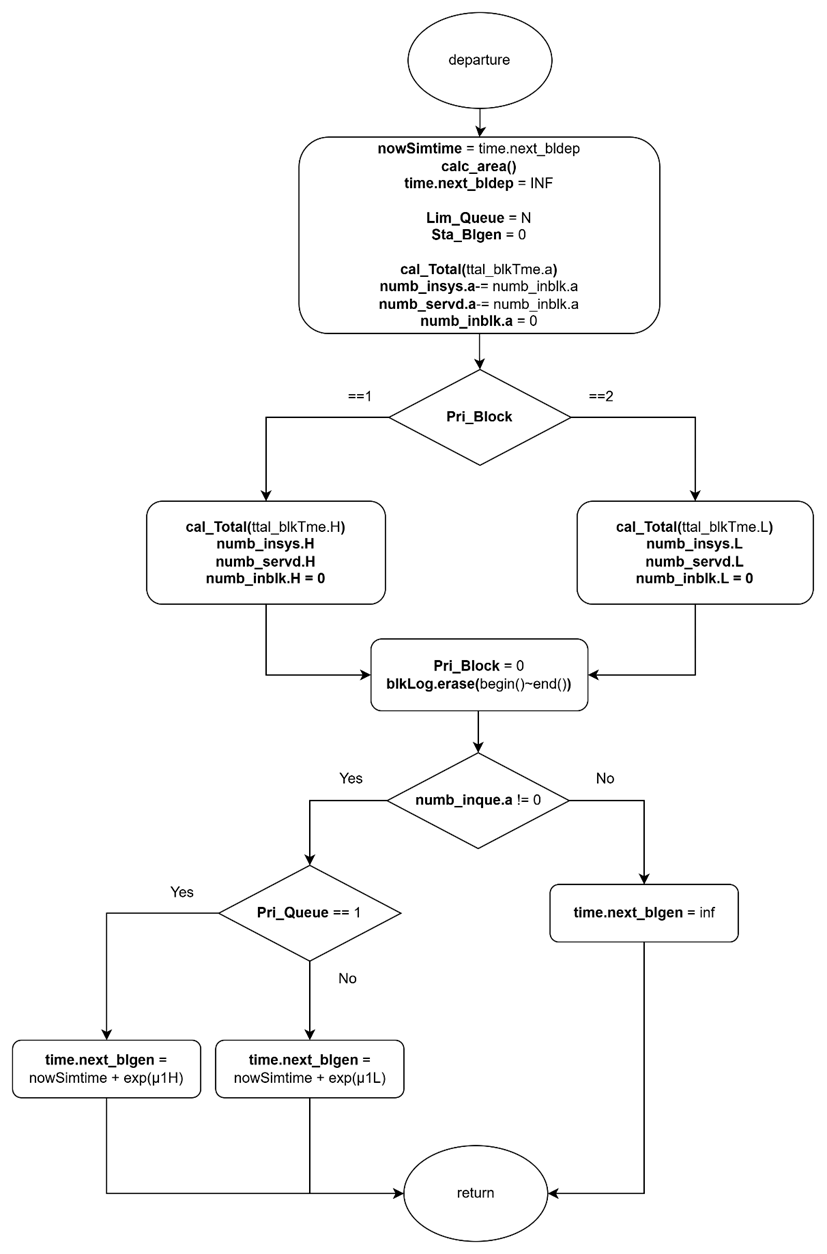


Figure ‑: Flow chart of block departure subprogram

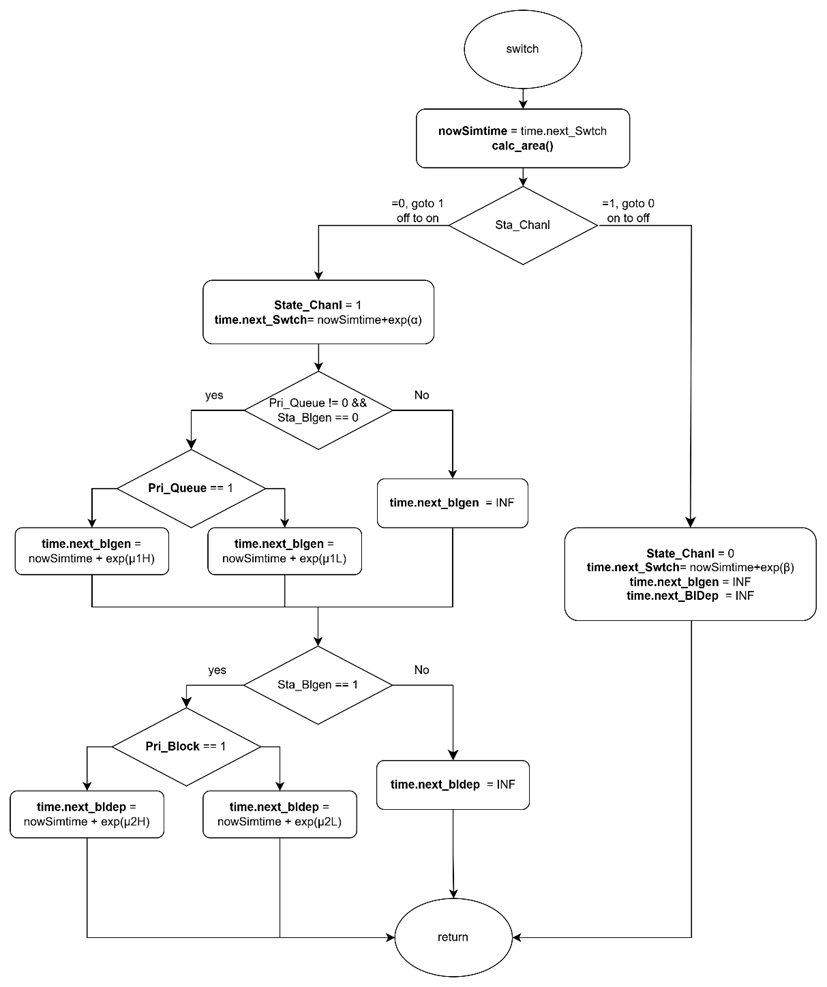


Figure ‑: Flow chart of switch subprogram



Figure ‑: Flow chart of impatient subprogram

### Performance Index

First of all, the average number of HP and LP customers in the whole system, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑47) |
|  |  | (4‑48) |

The average number of customers in the whole system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑49) |

Second, the average number of HP and LP customers in customer queue, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑50) |
|  |  | (4‑51) |

The average number of customers in customer queue, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑52) |

Third, the average number of HP and LP customers in block queue, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑53) |
|  |  | (4‑54) |

The average number of customers in block queue, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑55) |

Fourth, the blocking probability of HP and LP customers in the system, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑56) |
|  |  | (4‑57) |

The blocking probability of the system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑58) |

Fifth, the impatient probability of HP and LP customers in the system, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑59) |
|  |  | (4‑60) |

The impatient probability of the system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑61) |

Sixth, the throughput of HP and LP customers in the system, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑62) |
|  |  | (4‑63) |

The throughput of the system, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑64) |

Seventh, the average waiting time of the HP and LP customers in the customer queue, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑65) |
|  |  | (4‑66) |

The average waiting time in the customer queue, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑67) |

Eighth, the average waiting time of the HP and LP customers in the block queue, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑68) |
|  |  | (4‑69) |

The average waiting time in the block queue, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑70) |

Ninth, the average waiting time of the HP and LP customers in the system, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑71) |
|  |  | (4‑72) |

The average waiting time in the block queue, denoted by is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑73) |

Finally, the average number of HP and LP blocks participating in the consensus process per unit of time, denoted by and , respectively, is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑74) |
|  |  | (4‑75) |

The average number of blocks participating in the consensus process per unit of time within a block, denoted by , is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4‑76) |

# Numerical Results

In this chapter, we present the numerical results derived from both the analytical model and the simulation model, covering four distinct blockchain queuing scenarios. Each scenario has two queues, which are customer queue and the block queue, operating under varying combinations of customer class structures and impatience behavior.

The first scenario models a single-class customer system without impatience, serving as a baseline configuration with First-Come-First-Served (FCFS) discipline and no abandonment. The second scenario introduces two classes of customers with non-preemptive priority, distinguishing HP and LP customers in both queuing and service procedures. In the third scenario, we revisit the single-class setting while incorporating impatience behavior, where customers may abandon the system after a random impatience threshold. Finally, the fourth scenario combines both priority and impatience, modeling a two-class customer system with distinct abandonment rates and non-preemptive priority rules.

Across all scenarios, the blockchain service is influenced by ON/OFF operational states and employs a partial batch policy during block generation. Performance metrics such as throughput, blocking probability, waiting time, and impatient rate (where applicable) are computed and compared under varying parameter configurations. These results provide a comprehensive view of how priority, impatience, and system reliability jointly impact the overall performance of blockchain-based queuing systems.

## Scenario 1: Single-Class Customer without Impatience

The default values are as provided as below: , , , . The maximum capacity of the system is , and the maximum block size is .

### Block Size

Figure 5‑1 to Figure 5‑6 show the relationship between various performance metrics and the block size . Both simulation results and analytical results are shown for comparison.

Figure 5‑1 illustrates the impact of the block size on the average waiting time in the customer queue (). As increases, decreases significantly, particularly at smaller block size. This is because larger blocks allow more customers to be served per service cycle, thereby reducing the time customers spend waiting in the queue. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑2 illustrates the impact of the block size on the average waiting time in the block queue (). As increases, remains nearly constant. This indicates that the time each block spends in the consensus queue is determined by the consensus rate and system state transition rate, and is independent of block size. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑3 illustrates the impact of the block size on the average waiting time in the system (). As increases, decreases significantly, particularly at smaller block size. This is because larger blocks allow more customers to be served per service cycle, thereby reducing the time customers spend waiting in the queue. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑4 illustrates the impact of the block size on the average number of customers in the block queue (). As increases, initially grows and then stabilizes around constant value. This indicates that although larger blocks permit more customers per batch, the average block occupancy tends to saturate when the customer arrival rate is equal to the effective service rate of the customer queue, where the effective service rate of the customer queue is dependent on the block generation rate, the system transition rate, and the average block size. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑5 illustrates the impact of the block size on the blocking probability (). As increases, steadily decreases. This is because larger blocks allow more customers to be served per block generation cycle, thereby reducing the chance of the customer queue reaching its capacity limit. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑6 illustrates the impact of the block size on the system throughput (). As increases, rises rapidly at first and then gradually saturates. This is because larger blocks enable more customers to be processed per consensus cycle, but the throughput eventually approaches a limit determined by the customer arrival rate, which is less than the system processing capacity. The system processing capacity is decided by the maximum block size, the block generation rate, consensus rate, and system state transition rate. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure ‑: block size vs. average waiting time in the customer queue

Figure ‑: Block size vs. average waiting time in the block queue

Figure ‑: Block size vs. average waiting time in the system

Figure ‑: Block size vs. average number of customers in block queue

Figure ‑: Block size vs. blocking probability

Figure ‑: Block size vs. system throughput

### Arrival Rate

Figure 5‑7 to Figure 5‑12 show the relationship between various performance metrics and the arrival rate . Both simulation results and analytical results are shown for comparison.

Figure 5‑7 illustrates the impact of the arrival rate on the average waiting time in the customer queue (). As increases, increases steadily. This is because higher arrival rate leads to more customers entering the system, causing increased congestion and longer queuing delays before customers can be batched into blocks. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑8 illustrates the impact of the arrival rate on the average waiting time in the block queue (). As increases, remains nearly constant. This indicates that the time each block spends in the consensus queue is determined by the consensus rate and system transition rate, and is independent of the arrival rate. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑9 illustrates the impact of the arrival rate on the average waiting time in the system (). As increases, increases steadily. This is because higher arrival rate leads to more customers entering the system, causing increased congestion and longer queuing delays before customers depart from the system. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑10 illustrates the impact of the arrival rate on the average number of customers in the block queue (). As increases, increases steadily. This is because a higher arrival rate leads to more frequent block formation and more customers being accumulated in each block, increasing the average number of customers waiting for consensus. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑11 illustrates the impact of the arrival rate on the blocking probability (). As increases, rises sharply, specially beyond . This is because a higher arrival rate leads to more customers being accumulated in the customer queue, increasing the chance that incoming customers are blocked due to limited queue capacity. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑12 illustrates the impact of the arrival rate on the system throughput (). As increases, rises rapidly at first and then gradually saturates. This is because higher arrival rates supply more customers into the system, but throughput eventually becomes limited by the system service capacity, which is decided by the maximum block size, the block generation rate, the consensus rate, and system transition rate. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure ‑: Arrival rate vs. average waiting time in the customer queue

Figure ‑: Arrival rate vs. average waiting time in the block queue

Figure ‑: Arrival rate vs. average waiting time in the system

Figure ‑: Arrival rate vs. average number of customers in block queue

Figure ‑: Arrival rate vs. blocking probability

Figure ‑: Arrival rate vs. throughput

### Block Generation Rate

Figure 5‑13 to Figure 5‑18 show the relationship between various performance metrics and the block generation rate . Both simulation results and analytical results are shown for comparison.

Figure 5‑13 illustrates the impact of the block generation rate on the average waiting time in the customer queue (). As increases, decreases significantly. This is because higher block generation rates allow customers to be grouped and processed more frequently, which reduces congestion in the customer queue. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑14 illustrates the impact of the block generation rate on the average waiting time in the block queue (). As increases, remains nearly constant. This indicates that the time each block spends in the consensus queue is determined by the consensus rate and system transition rate, and is independent of the block generation rate. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑15 illustrates the impact of the block generation rate on the average waiting time in the system (). As increases, decreases steadily. This is because higher block generation rates allow customers to be grouped and processed more frequently, which reduces congestion in the customer queue. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑16 illustrates the impact of the block generation rate on the average number of customers in the block queue (). As increases, initially grows and then stabilizes around constant value. This indicates that although more frequent block generation can expedite customers service, the average block occupancy tends to saturate because of the arrival rate and the effective service rate reached a state of equilibrium. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑17 illustrates the impact of the block generation rate on the blocking probability (). As increases, decreases rapidly. This is because higher block generation rates allow customers to be served more frequently, reducing the possibility that the customer queue reaches its capacity and causes incoming arrivals to be blocked. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑18 illustrates the impact of the block generation rate on the system throughput (). As increases, rises rapidly at first and then gradually saturates. This is because higher block generation rates enable more customers to be processed per consensus cycle, but the throughput eventually approaches a limit determined by the customer arrival rate, which is less than the system processing capacity. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure ‑: Block generation rate vs. average waiting time in the customer queue

Figure ‑: Block generation rate vs. average waiting time in the block queue

Figure ‑: Block generation rate vs. average waiting time in the system

Figure ‑: Block generation rate vs. average number of customers in block queue

Figure ‑: Block generation rate vs. blocking probability

Figure ‑: Block generation rate vs. system throughput

### Consensus Rate

Figure 5‑19 to Figure 5‑24 show the relationship between various performance metrics and the consensus rate . Both simulation results and analytical results are shown for comparison.

Figure 5‑19 illustrates the impact of the consensus rate on the average waiting time in the customer queue (). As increases, decrease steadily. This is because a higher consensus rate shortens the time block spend in the consensus queue, enabling faster turnover and more frequent admission of waiting customers from the customer queue. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑20 illustrates the impact of the consensus rate on the average waiting time in the block queue (). As increases, decrease significantly. This is because a faster consensus rate allows blocks to be processed more quickly, thereby reducing the time that blocks spend waiting in the queue. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑21 illustrates the impact of the consensus rate on the average waiting time in the system (). As increases, decrease significantly. This is because faster consensus processing reduces delays in the block queue, which in turn accelerates the overall service flow and shortens the total time customers spend in the system. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑22 illustrates the impact of the consensus rate on the average number of customers in the block queue (). As increases, decrease significantly. This is because a higher consensus rate enables faster processing of blocks, which reduces queue accumulation and lowers the . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑23 illustrates the impact of the consensus rate on the blocking probability (). As increases, decrease rapidly. This is because faster consensus rate enables faster processing of blocks, and lowers the probability of reaching the queue capacity that triggers blocking. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑24 illustrates the impact of the consensus rate on the system throughput (). As increases, increase rapidly at first and then gradually saturates. This is because higher consensus rate allows blocks to be processed more efficiently, but the throughput eventually approaches a limit determined by the customer arrival rate, which is less than the system processing capacity. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure ‑: Consensus rate vs. average waiting time in the customer queue

Figure ‑: Consensus rate vs. average waiting time in the block queue

Figure ‑: Consensus rate vs. average waiting time in the system

Figure ‑: Consensus rate vs. average number of customers in block queue

Figure ‑: Consensus rate vs. blocking probability

Figure ‑: Consensus rate vs. system throughput

### Transition Rate (ON to OFF)

Figure 5‑25 to Figure 5‑30 show the relationship between various performance metrics and the transition rate from ON to OFF . Both simulation results and analytical results are shown for comparison.

Figure 5‑25 illustrates the impact of the transition rate on the average waiting time in the customer queue (). As increases, increases steadily. This is because more frequent transitions from ON to OFF reduce the availability of block generation service, causing longer queueing delays for arriving customers. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑26 illustrates the impact of the transition rate on the average waiting time in the block queue (). As increases, increase steadily. This is because more frequent service interruptions delay consensus processing, resulting in longer waiting times for customer(s) in block queue. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑27 illustrates the impact of the transition rate on the average waiting time in the system (). As increases, increase steadily. This is because more frequent service interruptions caused by transitions to the OFF state reduce overall availability of block generation and consensus service, leading to longer queueing delays for customers in the system. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑28 illustrates the impact of the transition rate on the average number of customers in the block queue (). As increases, increases steadily. This is because more frequent service interruptions of block generation processing cause more customers to wait in the customer queue while forming batches from the customer queue. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑29 illustrates the impact of the transition rate on the blocking probability (). As increases, increases steadily. This is because more frequent service interruptions reduce the system’s capacity to process customers, which increases the probability that the customer queue reaches its capacity and causes incoming arrivals to be blocked. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑30 illustrates the impact of the transition rate on the system throughput (). As increases, decreases gradually. This is because more frequent service interruptions reduce the chance for block generation and consensus processing, thereby limiting the rate at which customers are served and ultimately lowering the overall system throughput. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure ‑: Transition rate vs. average waiting time in the customer queue in the system

Figure ‑: Transition rate vs. average waiting time in the block queue

Figure ‑: Transition rate vs. average waiting time in the system

Figure ‑: Transition rate vs. average number of customers in block queue

Figure ‑: Transition rate vs. blocking probability

Figure ‑: Transition rate vs. system throughput

## Scenario 2: Two-Class Customer without Impatience

The default values are as provided as below: , , , , , , . The maximum capacity of the system is , and the maximum block size is .

### Block Size

Figure 5‑31 to Figure 5‑36 show the relationship between various performance metrics and the block size . Both simulation results and analytical results are shown for comparison.

Figure 5‑31 illustrates the impact of the block size on the average waiting times in the customer queue for HP, LP, and overall customers. As increases, the decreases. The reduction is more pronounced for , while remain consistently low. This is because larger blocks allow more customers to be served per service cycle, thereby reducing the time, especially for LP customers who tend to experience longer delays when is small. In addition, the is much smaller than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑32 illustrates the impact of the block size on the average waiting times in the block queue for HP, LP, and overall customers. As increases, the average waiting time in the block queue remains nearly constant for all priority levels. This indicates that the time each block spends in the consensus queue is determined by the consensus rate and system state transition rate, and is independent of block size. In addition, the is smaller than . This is because is larger than . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑33 illustrates the impact of the block size on the average waiting times in the system for HP, LP, and overall customers. As increases, the decreases. The decline is especially significant for LP customers, while the remains relatively constant. This is because larger blocks allow more customers to be served per service cycle, which benefits LP customers who are otherwise delayed by the non-preemptive priority mechanism. In addition, the is much smaller than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue and is larger than . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑34 illustrates the impact of the block size on the average numbers of customers in the block queue for HP, LP, and overall customers. As increases, the average number of customers in the block queue rises gradually across all priority levels. The increase is most noticeable for and , while the remains relatively low and stable. This indicates that although larger blocks permit more customers per batch, the average block occupancy tends to saturate when the customer arrival rate is equal to the effective service rate of the customer queue. In addition, is smaller than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue and the HP customers have faster consensus rate than LP customers in the block queue, and therefore more LP customers remain waiting in the customer queue before being batched. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑35 illustrates the impact of the block size on the blocking probabilities for HP, LP, and overall customers. As increases, the blocking probability decreases across all priority levels. The decline is more pronounced for , which is initially much higher and drops significantly with increasing . This is because larger blocks allow more customers to be served per block generation cycle, thereby reducing the chance of the customer queue reaching its capacity limit, especially for LP customers who are more likely to be blocked under limited queue capacity. In addition, is smaller than . This is because the capacity limit of the customer queue for the HP customers is no smaller than that for LP customers. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑36 illustrates the impact of the block size on the system throughputs for HP, LP, and overall customers. As increases, the system throughput increases across all priority levels and then gradually saturates. Both and increase with , with the growth being more significant for LP customers. This is because larger blocks enable more customers to be processed per consensus cycle. However, the throughput eventually approaches a limit determined by the customer arrival rate, which is less than the system processing capacity. In addition, is smaller than . This is because the customer arrival rate of the HP customers is smaller than that of LP customers. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure ‑: Block size vs. average waiting time in the customer queue

Figure ‑: Block size vs. average waiting time in the block queue

Figure ‑: Block size vs. average waiting time in the system

Figure ‑: Block size vs. average number of customers in block queue

Figure ‑: Block size vs. blocking probability

Figure ‑: Block size vs. system throughput

### HP Arrival Rate

Figure 5‑37 to Figure 5‑42 show the relationship between various performance metrics and the arrival rate of HP customers . Both simulation results and analytical results are shown for comparison.

Figure 5‑37 illustrates the impact of the arrival rate of HP customers on the average waiting times in the customer queue for HP, LP, and overall customers. As increases, the increases steadily. The rise is mainly due to the significant increase in , while remains nearly constant. This is because more HP arrivals dominate the queue under the non-preemptive priority mechanism, causing LP customers to wait longer in the customer queue. In addition, the is much shorter than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑38 illustrates the impact of the arrival rate of HP customers on the average waiting times in the block queue for HP, LP, and overall customers. As increases, and remains nearly constant. This indicates that the time each block spends in the consensus queue is determined by the associated consensus rate and system transition rate, and is independent of . In addition, is smaller than . This is because is larger than . Furthermore, as increases, decreases. This is because as increases, more HP blocks are formed and the consensus rate of HP customers is larger than that of LP customers. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑39 illustrates the impact of the arrival rate of HP customers on the average waiting times in the system for HP, LP, and overall customers. As increases, the increases steadily. The rise is mainly due to the significant increase in , while remains nearly constant. This is because more dominate the queue under the non-preemptive priority mechanism, causing LP customers to spend more time in the system. In addition, is much smaller than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue and is larger than . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑40 illustrates the impact of the arrival rate of HP customers on the average numbers of customers in the block queue for HP, LP, and overall customers. As increases, the remains relatively stable, but with diverging trends across priority class. Specifically, increases and decreases. This behavior reflects the shift in queue composition under the non-preemptive priority mechanism, where more HP customers are admitted into the system while LP customers are blocked earlier or delayed at the customer queue. Thus, more HP blocks and less LP blocks are formed. In addition, is smaller than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue and the HP customers have faster consensus rate than LP customers in the block queue, and therefore more LP customers remain waiting in the customer queue before being batched. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑41 illustrates the impact of the arrival rate of HP customers on the blocking probabilities for HP, LP, and overall customers. As increases, the blocking probability increases across all priority levels. The rise is most significant for , who face greater difficulty being admitted into the system due to the increased presence of HP arrivals. This trend reflects the effect of the non-preemptive priority mechanism, where HP customers dominate the queue and are less probability to be blocked, while LP customers experience higher blocking rates as system congestion intensifies. In addition, is smaller than . This is because the capacity limit of the customer queue for the HP customers is no smaller than that for LP customers. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑42 illustrates the impact of the arrival rate of HP customers on the system throughputs for HP, LP, and overall customers. As increases, increases and decreases. The remains relatively stable, as the gain in compensates for the loss in . This behavior reflects the shift in resource allocation under the non-preemptive priority mechanism, where increasing leads to more system capacity being devoted to HP customers at the expense of LP ones. In addition, is smaller than . This is because the customer arrival rate of the HP customers is smaller than that of LP customers. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure ‑: HP arrival rate vs. average waiting time in the customer queue

Figure ‑: HP arrival rate vs. average waiting time in the block queue

Figure ‑: HP arrival rate vs. average waiting time in the system

Figure ‑: HP arrival rate vs. average number of customers in block queue

Figure ‑: HP arrival rate vs. blocking probability

Figure ‑: HP arrival rate vs. throughput

### HP Block Generation Rate

Figure 5‑43 to Figure 5‑48 show the relationship between various performance metrics and the block generation rate of high priority customers . Both simulation results and analytical results are shown for comparison.

Figure 5‑43 illustrates the impact of the block generation rate of HP customers on the average waiting times in the customer queue for HP, LP, and overall customers. As increases, the average waiting time in the customer queue decreases across all priority levels. The decline is more substantial for LP customers, who benefit from the increased service opportunities enabled by faster block generation. Although HP customers also experience shorter waiting times, their improvement is less pronounced since their queuing delay is already low. In addition, the is much smaller than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑44 illustrates the impact of the block generation rate of HP customers on the average waiting times in the block queue for HP, LP, and overall customers. As increases, the average waiting time in the block queue remains nearly constant across all priority levels. This indicates that the time each block spends in the consensus queue is determined by the associated consensus rate and system transition rate, and is independent of the block generation rate. In addition, the is smaller than . This is because is larger than . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑45 illustrates the impact of the block generation rate of HP customers on the average waiting times in the system for HP, LP, and overall customers. As increases, average waiting time in the system decreases across all priority levels. The rise is primarily contributed by , while HP customers also benefit from more frequent block formation. This is because higher block generation rates allow customers to be grouped and processed more frequently, which reduces congestion in the customer queue. In addition, the is much smaller than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue and is larger than . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑46 illustrates the impact of the block generation rate of HP customers on the average numbers of customers in the block queue for HP, LP, and overall customers. As increases, the gradually increases. The rise is primarily contributed by , while increases only slightly and remains at a relatively low level. This is because a higher allows HP customers to be processed more quickly, which indirectly leads to more LP customers forming batches. In addition, is smaller than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue and therefore more LP customers remain waiting in the customer queue before being batched. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑47 illustrates the impact of the block generation rate of HP customers on the blocking probabilities for HP, LP, and overall customers. As increases, the blocking probability decreases across all priority levels. This is because the higher block generation rate allows HP customers to be served more frequently, which in turn release the capacity in the customer queue for LP customers. As a result, the probability that LP customers are blocked is reduced. In addition, is smaller than . This is because the capacity limit of the customer queue for the HP customers is no smaller than that for LP customers. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑48 illustrates the impact of the block generation rate of HP customers on the system throughputs for HP, LP, and overall customers. As increases, the system throughput increases across all priority levels and then gradually saturates. The rise is primarily contributed by , which increases more significantly due to the release of queue capacity made possible by faster processing of HP blocks. In contrast, eventually approaches a limit determined by . In addition, is smaller than . This is because the customer arrival rate of the HP customers is smaller than that of LP customers. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure ‑: HP block generation rate vs. average waiting time in the customer queue

Figure ‑: HP block generation rate vs. average waiting time in the block queue

Figure ‑: HP block generation rate vs. average waiting time in the system

Figure ‑: HP block generation rate vs. average number of customers in block queue

Figure ‑: HP block generation rate vs. blocking probability

Figure ‑: HP block generation rate vs. system throughput

### HP Consensus Rate

Figure 5‑49 to Figure 5‑54 show the relationship between various performance metrics and the consensus rate of HP customers . Both simulation results and analytical results are shown for comparison.

Figure 5‑49 illustrates the impact of the consensus rate of HP customers on the average waiting times in the customer queue for HP, LP, and overall customers. As increases, the decreases. The reduction is more pronounced for , while remains relatively stable. This is because higher allows HP blocks to complete consensus more quickly, thereby shortening the duration that HP customers occupy system capacity. As a result, more capacity becomes available for LP customers, so that reducing . In addition, the is much smaller than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑50 illustrates the impact of the consensus rate of HP customers on the average waiting times in the block queue for HP, LP, and overall customers. As increases, the decreases slightly. The decline is primarily contributed by , while remains nearly constant. This is because a higher allows HP blocks to complete consensus more quickly, reducing the amount of time the HP customers spend waiting in the block queue. Since the consensus rate of LP customers is not affected, their waiting time remains unchanged. In addition, at , is noticeably higher than , but the two curves intersect around , after which becomes lower. This crossover occurs because starts lower than the fixed , and increasing improves HP processing speed. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑51 illustrates the impact of the consensus rate of HP customers on the average waiting times in the system for HP, LP, and overall customers. As increases, the average waiting time in the system decreases steadily for all priority levels. This is because faster reduces delays in the block queue, thereby improving system efficiency. While also decreases slightly as system capacity is released from HP customers. This trend highlights how improving consensus efficiency for HP customers can enhance overall system flow and reduce and . In addition, the is much smaller than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑52 illustrates the impact of the consensus rate of HP customers on the average numbers of customers in the block queue for HP, LP, and overall customers. As increases, the slightly decreases. This change is mainly driven by a noticeable reduction in , while gradually increases due to the admission of more LP customers as system capacity is released by faster . This reflects how increasing can reduce queue capacity for HP customers while indirectly increasing . In addition, is smaller than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue and is larger than , and therefore more LP customers remain waiting in the customer queue before being batched. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑53 illustrates the impact of the consensus rate of HP customers on the blocking probabilities for HP, LP, and overall customers. As increases, the blocking probability decreases across all priority levels. This decline is more significant for HP customers, whose blocks are processed more rapidly with higher , resulting in fewer delays and fewer blocked arrivals. Also, faster processing of HP customers indirectly frees up capacity in the customer queue, reducing the as well. In addition, is smaller than . This is because the capacity limit of the customer queue for the HP customers is no smaller than that for LP customers. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑54 illustrates the impact of the consensus rate of HP customers on the system throughputs for HP, LP, and overall customers. As increases, the system throughput increases across all priority levels and then gradually saturates. The rise is primarily contributed by , which increases more significantly due to the release of queue capacity made possible by faster processing of HP blocks. In contrast, eventually approaches a limit determined by . In addition, is smaller than . This is because the customer arrival rate of the HP customers is smaller than that of LP customers. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure ‑: HP consensus rate vs. average waiting time in the customer queue

Figure ‑: HP consensus rate vs. average waiting time in the block queue

Figure ‑: HP consensus rate vs. average waiting time in the system

Figure ‑: HP consensus rate vs. average number of customers in block queue

Figure ‑: HP consensus rate vs. blocking probability

Figure ‑: HP consensus rate vs. system throughput

### Transition Rate (ON to OFF)

Figure 5‑55 to Figure 5‑60 show the relationship between various performance metrics and the transition rate . Both simulation results and analytical results are shown for comparison.

Figure 5‑55 illustrates the impact of the transition rate on the average waiting times in the customer queue for HP, LP, and overall customers. As increases, the average waiting time in the customer queue rises steadily across all priority levels. The increase is more pronounced for LP customers, who are more affected by interruptions in service. This is because more frequent transitions from ON to OFF reduce the availability of block generation service, causing longer queueing delays for arriving customers, especially for customers with lower priority. In addition, the is much smaller than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑56 illustrates the impact of the transition rate on the average waiting times in the block queue for HP, LP, and overall customers. As increases, the average waiting time in the block queue increase steadily across all priority levels. This is because more frequent service interruptions delay consensus processing, resulting in longer waiting times for customer(s) in block queue. This effect is observed for both high- and LP customers, with LP customers experiencing slightly longer delay. In addition, the is smaller than . This is because is larger than . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑57 illustrates the impact of the transition rate on the average waiting times in the system for HP, LP, and overall customers. As increases, the average waiting time in the system increase steadily across all priority levels. The increase is more significant for , while increases slightly. This is because more frequent service interruptions caused by transitions to the OFF state reduce overall availability of block generation and consensus service, leading to longer queueing delays for customers in the system. In addition, the is much smaller than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue and is larger than . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑58 illustrates the impact of the transition rate on the average numbers of customers in the block queue for HP, LP, and overall customers. As increases, the average number of customers in the block queue increase steadily across all priority levels. This is because more frequent service interruptions of block generation processing cause more customers to wait in the customer queue while forming batches from the customer queue. In addition, is smaller than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue and is larger than , and therefore more LP customers remain waiting in the customer queue before being batched. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑59 illustrates the impact of the transition rate on the blocking probabilities for HP, LP, and overall customers. As increases, the blocking probability increase steadily across all priority levels. The rise is more pronounced for , while increases at a slower rate. This is because more frequent service interruptions reduce the system’s capacity to process customers, which increases the probability that the customer queue reaches its capacity and causes incoming arrivals to be blocked. In addition, is smaller than . This is because the capacity limit of the customer queue for the HP customers is no smaller than that for LP customers. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑60 illustrates the impact of the transition rate on the system throughputs for HP, LP, and overall customers. As increases, the system throughput decreases gradually across all priority levels. This is because more frequent service interruptions reduce the chance for block generation and consensus processing, thereby limiting the rate at which customers are served and ultimately lowering the . The decline is more pronounced for , whose service opportunities are more severely impacted by limited availability, while remains relatively stable. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure ‑: Transition rate vs. average waiting time in the customer queue in the system

Figure ‑: Transition rate vs. average waiting time in the block queue

Figure ‑: Transition rate vs. average waiting time in the system

Figure ‑: Transition rate vs. average number of customers in block queue

Figure ‑: Transition rate vs. blocking probability

Figure ‑: Transition rate vs. system throughput

## Scenario 3: Single-Class Customer with Impatience

The default values are as provided as below: , , , , . The maximum capacity of the system is , and the maximum block size is .

### Block Size

Figure 5‑61 to Figure 5‑67 show the relationship between various performance metrics and the block size . Both simulation results and analytical results are shown for comparison.

Figure 5‑61 illustrates the impact of the block size on the average waiting time in the customer queue (). As increases, decreases significantly, particularly at smaller block size. This is because larger blocks allow more customers to be served per service cycle, thereby reducing the time customers spend waiting in the queue. Additionally, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which further suppresses queue buildup and contributes to the decline in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑62 illustrates the impact of the block size on the average waiting time in the block queue (). As increases, remains nearly constant. This indicates that the time each block spends in the consensus queue is determined by the consensus rate and system state transition rate, and is independent of block size. Furthermore, with impatience is the same as that without impatience. This is because once a block is formed, impatience mechanism has no effect on it. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑63 illustrates the impact of the block size on the average waiting time in the system (). As increases, decreases significantly, particularly at smaller block size. This is because larger blocks allow more customers to be served per service cycle, thereby reducing the time customers spend waiting in the queue. Additionally, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which further suppresses queue buildup and contributes to the decline in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑64 illustrates the impact of the block size on the average number of customers in the block queue (). As increases, initially grows and then stabilizes around constant value. This indicates that although larger blocks permit more customers per batch, the average block occupancy tends to saturate when the customer arrival rate is equal to the effective service rate of the customer queue, where the effective service rate of the customer queue is dependent on the block generation rate, the system transition rate, and the average block size. Additionally, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which contributes to a reduction in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑65 illustrates the impact of the block size on the blocking probability (). As increases, steadily decreases. This is because larger blocks allow more customers to be served per block generation cycle, thereby reducing the chance of the customer queue reaching its capacity limit. Additionally, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which contributes to a reduction in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑66 illustrates the impact of the block size on the system throughput (). As increases, rises rapidly at first and then gradually saturates. This is because larger blocks enable more customers to be processed per consensus cycle, but the throughput eventually approaches a limit determined by the customer arrival rate and the impatient rate, which is less than the system processing capacity. The system processing capacity is decided by the maximum block size, the block generation rate, consensus rate, and system state transition rate. As a result, with impatience is smaller than that without impatience. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑67 illustrates the impact of the block size on the impatience probability (). As increases, steadily decreases. This is because larger blocks allow more customers to be served in each service cycle, which reduces the waiting time in the customer queue. As a result, the probability that customers reach their impatience threshold and leave the system becomes lower. As a result, with impatience is larger than without impatience. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure ‑: Block size vs. average waiting time in the customer queue

Figure ‑: Block size vs. average waiting time in the block queue

Figure ‑: Block size vs. average waiting time in the system

Figure ‑: Block size vs. average number of customers in block queue

Figure ‑: Block size vs. blocking probability

Figure ‑: Block size vs. system throughput

Figure ‑: Block size vs. the impatient probability

### Arrival Rate

Figure 5‑68 to Figure 5‑74 show the relationship between various performance metrics and the arrival rate . Both simulation results and analytical results are shown for comparison.

Figure 5‑68 illustrates the impact of the arrival rate on the average waiting time in the customer queue (). As increases, increases steadily. This is because higher arrival rate leads to more customers entering the system, causing increased congestion and longer queuing delays before customers can be batched into blocks. Additionally, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which further suppresses queue buildup and contributes to the decline in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑69 illustrates the impact of the arrival rate on the average waiting time in the block queue (). As increases, remains nearly constant. This indicates that the time each block spends in the consensus queue is determined by the consensus rate and system transition rate, and is independent of the arrival rate. Furthermore, with impatience is the same as that without impatience. This is because once a block is formed, impatience mechanism has no effect on it. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑70 illustrates the impact of the arrival rate on the average waiting time in the system (). As increases, increases steadily. This is because higher arrival rate leads to more customers entering the system, causing increased congestion and longer queuing delays before customers depart from the system. Additionally, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which further suppresses queue buildup and contributes to the decline in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑71 illustrates the impact of the arrival rate on the average number of customers in the block queue (). As increases, increases steadily. This is because a higher arrival rate leads to more frequent block formation and more customers being accumulated in each block, increasing the average number of customers waiting for consensus. Additionally, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which contributes to a reduction in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑72 illustrates the impact of the arrival rate on the blocking probability (). As increases, rises sharply, specially beyond . This is because a higher arrival rate leads to more customers being accumulated in the customer queue, increasing the chance that incoming customers are blocked due to limited queue capacity. Additionally, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which contributes to a reduction in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑73 illustrates the impact of the arrival rate on the system throughput (). As increases, rises rapidly at first and then gradually saturates. This is because higher arrival rates supply more customers into the system, but throughput eventually becomes limited by the impatience rate and the system service capacity, which is decided by the maximum block size, the block generation rate, the consensus rate, and system transition rate. As a result, with impatience is smaller than that without impatience. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑74 illustrates the impact of the arrival rate on the impatience probability (). As increases, increases steadily. This is because a higher arrival rate leads to increased queue congestion and longer waiting times in the customer queue. Consequently, more customers are likely to reach their impatience threshold and leave the system before being served. As a result, with impatience is larger than without impatience. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure ‑: Arrival rate vs. average waiting time in the customer queue

Figure ‑: Arrival rate vs. average waiting time in the block queue

Figure ‑: Arrival rate vs. average waiting time in the system

Figure ‑: Arrival rate vs. average number of customers in block queue

Figure ‑: Arrival rate vs. blocking probability

Figure ‑: Arrival rate vs. throughput

Figure ‑: Arrival rate vs. the impatient probability

### Block Generation Rate

Figure 5‑75 to Figure 5‑81 show the relationship between various performance metrics and the block generation rate . Both simulation results and analytical results are shown for comparison.

Figure 5‑75 illustrates the impact of the block generation rate on the average waiting time in the customer queue (). As increases, decreases significantly. This is because higher block generation rates allow customers to be grouped and processed more frequently, which reduces congestion in the customer queue. Additionally, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which further suppresses queue buildup and contributes to the decline in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑76 illustrates the impact of the block generation rate on the average waiting time in the block queue (). As increases, remains nearly constant. This indicates that the time each block spends in the consensus queue is determined by the consensus rate and system transition rate, and is independent of the block generation rate. Furthermore, with impatience is the same as that without impatience. This is because once a block is formed, impatience mechanism has no effect on it. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑77 illustrates the impact of the block generation rate on the average waiting time in the system (). As increases, decreases steadily. This is because higher block generation rates allow customers to be grouped and processed more frequently, which reduces congestion in the customer queue. Additionally, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which further suppresses queue buildup and contributes to the decline in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑78 illustrates the impact of the block generation rate on the average number of customers in the block queue (). As increases, initially grows and then stabilizes around constant value. This indicates that although more frequent block generation can expedite customers service, the average block occupancy tends to saturate because of the arrival rate and the effective service rate reached a state of equilibrium. Additionally, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which contributes to a reduction in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑79 illustrates the impact of the block generation rate on the blocking probability (). As increases, decreases rapidly. This is because higher block generation rates allow customers to be served more frequently, reducing the possibility that the customer queue reaches its capacity and causes incoming arrivals to be blocked. Additionally, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which contributes to a reduction in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑80 illustrates the impact of the block generation rate on the system throughput (). As increases, rises rapidly at first and then gradually saturates. This is because higher block generation rates enable more customers to be processed per consensus cycle, but the throughput eventually approaches a limit determined by the customer arrival rate and the impatient rate, which is less than the system processing capacity. As a result, with impatience is smaller than that without impatience. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑81 illustrates the impact of the block generation rate on the impatience probability (). As increases, gradually decreases. A higher block generation rate allows customers to be grouped into blocks and served more frequently, thereby shortening their time in the customer queue. This reduces the chance of reaching the impatience threshold before service. As a result, with impatience is larger than without impatience. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure ‑: Block generation rate vs. average waiting time in the customer queue

Figure ‑: Block generation rate vs. average waiting time in the block queue

Figure ‑: Block generation rate vs. average waiting time in the system

Figure ‑: Block generation rate vs. average number of customers in block queue

Figure ‑: Block generation rate vs. blocking probability

Figure ‑: Block generation rate vs. system throughput

Figure ‑: Effect of block generation on the impatient probability

### Consensus Rate

Figure 5‑82 to Figure 5‑88 show the relationship between various performance metrics and the consensus rate . Both simulation results and analytical results are shown for comparison.

Figure 5‑82 illustrates the impact of the consensus rate on the average waiting time in the customer queue (). As increases, decrease steadily. This is because a higher consensus rate shortens the time block spend in the consensus queue, enabling faster turnover and more frequent admission of waiting customers from the customer queue. Additionally, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which further suppresses queue buildup and contributes to the decline in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑83 illustrates the impact of the consensus rate on the average waiting time in the block queue (). As increases, decrease significantly. This is because a faster consensus rate allows blocks to be processed more quickly, thereby reducing the time that blocks spend waiting in the queue. Furthermore, with impatience is the same as that without impatience. This is because once a block is formed, impatience mechanism has no effect on it. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑84 illustrates the impact of the consensus rate on the average waiting time in the system (). As increases, decrease significantly. This is because faster consensus processing reduces delays in the block queue, which in turn accelerates the overall service flow and shortens the total time customers spend in the system. Additionally, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which further suppresses queue buildup and contributes to the decline in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑85 illustrates the impact of the consensus rate on the average number of customers in the block queue (). As increases, decrease significantly. This is because a higher consensus rate enables faster processing of blocks, which reduces queue accumulation and lowers the . Additionally, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which contributes to a reduction in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑86 illustrates the impact of the consensus rate on the blocking probability (). As increases, decrease rapidly. This is because faster consensus rate enables faster processing of blocks, and lowers the probability of reaching the queue capacity that triggers blocking. Additionally, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which contributes to a reduction in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑87 illustrates the impact of the consensus rate on the system throughput (). As increases, increase rapidly at first and then gradually saturates. This is because higher consensus rate allows blocks to be processed more efficiently, but the throughput eventually approaches a limit determined by the customer arrival rate and the impatient rate, which is less than the system processing capacity. As a result, with impatience is smaller than that without impatience. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑88 illustrates the impact of the consensus rate on the system impatient probability (). As increases, steadily decreases. A higher consensus rate makes the consensus process more quickly, thereby lowering the probability of customers in customer queue reaching their impatience threshold. As a result, with impatience is larger than without impatience. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure ‑: Consensus rate vs. average waiting time in the customer queue

Figure ‑: Consensus rate vs. average waiting time in the block queue

Figure ‑: Consensus rate vs. average waiting time in the system

Figure ‑: Consensus rate vs. average number of customers in block queue

Figure ‑: Consensus rate vs. blocking probability

Figure ‑: Consensus rate vs. system throughput

Figure ‑: Consensus rate vs. the impatient probability

### Transition Rate (ON to OFF)

Figure 5‑89 to Figure 5‑95Figure 5‑94 show the relationship between various performance metrics and the transition rate from ON to OFF . Both simulation results and analytical results are shown for comparison.

Figure 5‑89 illustrates the impact of the transition rate on the average waiting time in the customer queue (). As increases, increases steadily. This is because more frequent transitions from ON to OFF reduce the availability of block generation service, causing longer queueing delays for arriving customers. Additionally, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which further suppresses queue buildup and contributes to the decline in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑90 illustrates the impact of the transition rate on the average waiting time in the block queue (). As increases, increase steadily. This is because more frequent service interruptions delay consensus processing, resulting in longer waiting times for customer(s) in block queue. Furthermore, with impatience is the same as that without impatience. This is because once a block is formed, impatience mechanism has no effect on it. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑91 illustrates the impact of the transition rate on the average waiting time in the system (). As increases, increase steadily. This is because more frequent service interruptions caused by transitions to the OFF state reduce overall availability of block generation and consensus service, leading to longer queueing delays for customers in the system. Additionally, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which further suppresses queue buildup and contributes to the decline in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑92 illustrates the impact of the transition rate on the average number of customers in the block queue (). As increases, increases steadily. This is because more frequent service interruptions of block generation processing cause more customers to wait in the customer queue while forming batches from the customer queue. Additionally, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which contributes to a reduction in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑93 illustrates the impact of the transition rate on the blocking probability (). As increases, increases steadily. This is because more frequent service interruptions reduce the system’s capacity to process customers, which increases the probability that the customer queue reaches its capacity and causes incoming arrivals to be blocked. Additionally, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which contributes to a reduction in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑94 illustrates the impact of the transition rate on the system throughput (). As increases, decreases gradually. This is because more frequent service interruptions reduce the chance for block generation and consensus processing. In addition, due to the impatience mechanism, customers are more likely to abandon the queue when waiting becomes longer, which contributes to a decline in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑95 illustrates the impact of the transition rate on the impatience probability (). As increases, increases steadily. This is because more frequent system on the OFF state which limits service availability, causing customers to wait longer in the queue and thus increasing the probability of reaching their impatience threshold. As a result, with impatience is larger than without impatience. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure ‑: Transition rate vs. average waiting time in the customer queue in the system

Figure ‑: Transition rate vs. average waiting time in the block queue

Figure ‑: Transition rate vs. average waiting time in the system

Figure ‑: Transition rate vs. average number of customers in block queue

Figure ‑: Transition rate vs. blocking probability

Figure ‑: Transition rate vs. system throughput

Figure ‑: Transition rate vs. the impatient probability

### Impatient Rate

Figure 5‑96 to Figure 5‑102 show the relationship between various performance metrics and the impatient rate . Both simulation results and analytical results are shown for comparison.

Figure 5‑96 illustrates the impact of the impatience rate on the average waiting time in the customer queue (). As increases, gradually decreases. This is because higher impatience rate makes customers more likely to abandon the customer queue once they reach their impatience threshold, thereby shortening the overall queue length and reducing the average waiting time in customer queue. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑97 illustrates the impact of the impatience rate on the average waiting time in the block queue (). As increases, remains nearly constant. This is because the impatience mechanism only affects customers while they are in the customer queue. Once a block is formed, they are no longer subject to abandonment due to impatience. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑98 illustrates the impact of the impatience rate on the average waiting time in the system (). As increases, steadily decreases. This is because higher impatience rate makes customers more likely abandon the customer queue once they reach their impatience threshold, which reduces congestion and lowers the overall time customers spend in the system. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑99 illustrates the impact of the impatience rate on the average number of customers in the block queue (). As increases, steadily decreases. This is because higher impatience rate makes customers more likely to abandon the customer queue once they reach their impatience threshold, reducing the number of customers that eventually form a block. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑100 illustrates the impact of the impatience rate on the blocking probability (). As increases, gradually decreases. This is because higher impatience rate makes customers more likely abandon the customer queue once they reach their impatience threshold, thereby reducing the probability that queue reaches its capacity and triggers blocking. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑101 illustrates the impact of the impatience rate on the system throughput (). As increases, decreases gradually. This is because higher impatience rate makes customers more likely abandon the customer queue once they reach their impatience threshold, which reduces the total number of customers successfully processed by the system. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑102 illustrates the impact of the impatience rate on the impatience probability (). As increases, increases significantly. This is because higher impatience rate makes customers more likely abandon the customer queue once they reach their impatience threshold. As a result, the proportion of customers abandoning the system increases, leading to a higher impatience probability. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure ‑: Impatient rate vs. average waiting time in the customer queue in the system

Figure ‑: Impatient rate vs. average waiting time in the block queue

Figure ‑: Impatient rate vs. average waiting time in the system

Figure ‑: Impatient rate vs. average number of customers in block queue

Figure ‑: Impatient rate vs. blocking probability

Figure ‑: Impatient rate vs. system throughput

Figure ‑: Impatient rate vs. the impatient probability

## Scenario 4: Two-Class Customer with Impatience

The default values are as provided as below: , , , , , , , , . The maximum capacity of the system is , and the maximum block size is .

### Block Size

Figure 5‑103 to Figure 5‑108 show the relationship between various performance metrics and the block size . Both simulation results and analytical results are shown for comparison.

Figure 5‑103 illustrates the impact of the block size on the average waiting times in the customer queue for HP, LP, and overall customers. As increases, the decreases. The reduction is more pronounced for , while remain consistently low. This is because larger blocks allow more customers to be served per service cycle, thereby reducing the time, especially for LP customers who tend to experience longer delays when is small. In addition, the is much smaller than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue. Furthermore, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which further suppresses queue buildup and contributes to the decline in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑104 illustrates the impact of the block size on the average waiting times in the block queue for HP, LP, and overall customers. As increases, the average waiting time in the block queue remains nearly constant for all priority levels. This indicates that the time each block spends in the consensus queue is determined by the consensus rate and system state transition rate, and is independent of block size. In addition, the is smaller than . This is because is larger than . Furthermore, with impatience is the same as that without impatience. This is because once a block is formed, impatience mechanism has no effect on it. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑105 illustrates the impact of the block size on the average waiting times in the system for HP, LP, and overall customers. As increases, the decreases. The decline is especially significant for LP customers, while the remains relatively constant. This is because larger blocks allow more customers to be served per service cycle, which benefits LP customers who are otherwise delayed by the non-preemptive priority mechanism. In addition, the is much smaller than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue and is larger than . Furthermore, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which further suppresses queue buildup and contributes to the decline in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑106 illustrates the impact of the block size on the average numbers of customers in the block queue for HP, LP, and overall customers. As increases, the average number of customers in the block queue rises gradually across all priority levels. The increase is most noticeable for and , while the remains relatively low and stable. This indicates that although larger blocks permit more customers per batch, the average block occupancy tends to saturate when the customer arrival rate is equal to the effective service rate of the customer queue. In addition, is smaller than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue and the HP customers have faster consensus rate than LP customers in the block queue, and therefore more LP customers remain waiting in the customer queue before being batched. Additionally, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which contributes to a reduction in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑107 illustrates the impact of the block size on the blocking probabilities for HP, LP, and overall customers. As increases, the blocking probability generally decreases. However, a slight increase is observed at across all priority levels. This is because, when the block queue is occupied, the effective capacity of the customer queue becomes , which may be too small when is large. With impatience, fewer users remain in the queue, resulting in smaller batches and slower queue clearance, which makes blocking more likely. Without impatience, fuller batches are formed, and the queue is cleared more efficiently before reaching the limit. The decline is more pronounced for , which is initially much higher and drops significantly with increasing . This is because larger blocks allow more customers to be served per block generation cycle, thereby reducing the chance of the customer queue reaching its capacity limit, especially for LP customers who are more likely to be blocked under limited queue capacity. In addition, is smaller than . This is because the capacity limit of the customer queue for the HP customers is no smaller than that for LP customers. Additionally, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which contributes to a reduction in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑108 illustrates the impact of the block size on the system throughputs for HP, LP, and overall customers. As increases, the system throughput increases across all priority levels and then gradually saturates. Both and increase with , with the growth being more significant for LP customers. This is because larger blocks enable more customers to be processed per consensus cycle. However, the throughput eventually approaches a limit determined by the customer arrival rate and the impatient rate, which is less than the system processing capacity. In addition, is smaller than . This is because the customer arrival rate of the HP customers is smaller than that of LP customers. As a result, with impatience is smaller than that without impatience. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑109 illustrates the impact of the block size on the impatient probabilities for HP, LP, and overall customers. As increases, the impatient probability across all priority levels. This is because larger blocks allow more customers to be served in each service cycle, which reduces the waiting time in the customer queue. As a result, the probability that customers reach their impatience threshold and leave the system becomes lower. In addition, is higher than , as LP customers are more likely to experience longer waits due to the non-preemptive priority discipline. As described above,  with impatience is larger than without impatience. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure ‑: Block size vs. average waiting time in the customer queue

Figure ‑: Block size vs. average waiting time in the block queue

Figure ‑: Block size vs. average waiting time in the system

Figure ‑: Block size vs. average number of customers in block queue

Figure ‑: Block size vs. blocking probability

Figure ‑: Block size vs. system throughput

Figure ‑: Block size vs. the impatient probability

### HP Arrival Rate

Figure 5‑110 to Figure 5‑115 show the relationship between various performance metrics and the arrival rate of HP customers . Both simulation results and analytical results are shown for comparison.

Figure 5‑110 illustrates the impact of the arrival rate of HP customers on the average waiting times in the customer queue for HP, LP, and overall customers. As increases, the increases steadily. The rise is mainly due to the significant increase in , while remains nearly constant. This is because more HP arrivals dominate the queue under the non-preemptive priority mechanism, causing LP customers to wait longer in the customer queue. In addition, the is much shorter than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue. Additionally, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which further suppresses queue buildup and contributes to the decline in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑111 illustrates the impact of the arrival rate of HP customers on the average waiting times in the block queue for HP, LP, and overall customers. As increases, and remains nearly constant. This indicates that the time each block spends in the consensus queue is determined by the associated consensus rate and system transition rate, and is independent of . In addition, is smaller than . This is because is larger than . Furthermore, as increases, decreases. This is because as increases, more HP blocks are formed and the consensus rate of HP customers is larger than that of LP customers. In addition, with impatience is the same as that without impatience. This is because once a block is formed, impatience mechanism has no effect on it. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑112 illustrates the impact of the arrival rate of HP customers on the average waiting times in the system for HP, LP, and overall customers. As increases, the increases steadily. The rise is mainly due to the significant increase in , while remains nearly constant. This is because more dominate the queue under the non-preemptive priority mechanism, causing LP customers to spend more time in the system. In addition, is much smaller than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue and is larger than . Furthermore, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which further suppresses queue buildup and contributes to the decline in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑113 illustrates the impact of the arrival rate of HP customers on the average numbers of customers in the block queue for HP, LP, and overall customers. As increases, the remains relatively stable, but with diverging trends across priority class. Specifically, increases and decreases. This behavior reflects the shift in queue composition under the non-preemptive priority mechanism, where more HP customers are admitted into the system while LP customers are blocked earlier or delayed at the customer queue. Thus, more HP blocks and less LP blocks are formed. In addition, is smaller than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue and the HP customers have faster consensus rate than LP customers in the block queue, and therefore more LP customers remain waiting in the customer queue before being batched. Furthermore, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which contributes to a reduction in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑114 illustrates the impact of the arrival rate of HP customers on the blocking probabilities for HP, LP, and overall customers. As increases, the blocking probability increases across all priority levels. The rise is most significant for , who face greater difficulty being admitted into the system due to the increased presence of HP arrivals. This trend reflects the effect of the non-preemptive priority mechanism, where HP customers dominate the queue and are less probability to be blocked, while LP customers experience higher blocking rates as system congestion intensifies. In addition, is smaller than . This is because the capacity limit of the customer queue for the HP customers is no smaller than that for LP customers. Furthermore, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which contributes to a reduction in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑115 illustrates the impact of the arrival rate of HP customers on the system throughputs for HP, LP, and overall customers. As increases, increases and decreases. The remains relatively stable, as the gain in compensates for the loss in . This behavior reflects the shift in resource allocation under the non-preemptive priority mechanism, where increasing leads to more system capacity being devoted to HP customers at the expense of LP ones. In addition, is smaller than . This is because the customer arrival rate of the HP customers is smaller than that of LP customers. Furthermore, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, reducing effective . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑116 illustrates the impact of the arrival rate of HP customers on the blocking probabilities for HP, LP, and overall customers. As increases, the impatience probability increases across all priority levels. The increase is primarily driven by , since a higher leads to more HP customers occupying the queue under the non-preemptive mechanism, causing longer delays for LP customers and increasing their probability of abandonment. In contrast, remains nearly constant. Consequently, is higher than , and with impatience is larger than without impatience. As described above, with impatience is larger than without impatience. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure ‑: HP arrival rate vs. average waiting time in the customer queue

Figure ‑: HP arrival rate vs. average waiting time in the block queue

Figure ‑: HP arrival rate vs. average waiting time in the system

Figure ‑: HP arrival rate vs. average number of customers in block queue

Figure ‑: HP arrival rate vs. blocking probability

Figure ‑: HP arrival rate vs. throughput

Figure ‑: HP arrival rate vs. the impatient probability

### HP Block Generation Rate

Figure 5‑117 to Figure 5‑122 show the relationship between various performance metrics and the block generation rate of high priority customers . Both simulation results and analytical results are shown for comparison.

Figure 5‑117 illustrates the impact of the block generation rate of HP customers on the average waiting times in the customer queue for HP, LP, and overall customers. As increases, the average waiting time in the customer queue decreases across all priority levels. The decline is more substantial for LP customers, who benefit from the increased service opportunities enabled by faster block generation. Although HP customers also experience shorter waiting times, their improvement is less pronounced since their queuing delay is already low. In addition, the is much smaller than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue. Furthermore, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which further suppresses queue buildup and contributes to the decline in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑118 illustrates the impact of the block generation rate of HP customers on the average waiting times in the block queue for HP, LP, and overall customers. As increases, the average waiting time in the block queue remains nearly constant across all priority levels. This indicates that the time each block spends in the consensus queue is determined by the associated consensus rate and system transition rate, and is independent of the block generation rate. In addition, the is smaller than . This is because is larger than . Furthermore, with impatience is the same as that without impatience. This is because once a block is formed, impatience mechanism has no effect on it. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑119 illustrates the impact of the block generation rate of HP customers on the average waiting times in the system for HP, LP, and overall customers. As increases, average waiting time in the system decreases across all priority levels. The rise is primarily contributed by , while HP customers also benefit from more frequent block formation. This is because higher block generation rates allow customers to be grouped and processed more frequently, which reduces congestion in the customer queue. In addition, the is much smaller than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue and is larger than . Furthermore, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which further suppresses queue buildup and contributes to the decline in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑120 illustrates the impact of the block generation rate of HP customers on the average numbers of customers in the block queue for HP, LP, and overall customers. As increases, the gradually increases. The rise is primarily contributed by , while increases only slightly and remains at a relatively low level. This is because a higher allows HP customers to be processed more quickly, which indirectly leads to more LP customers forming batches. In addition, is smaller than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue and therefore more LP customers remain waiting in the customer queue before being batched. Furthermore, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which contributes to a reduction in .Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑121 illustrates the impact of the block generation rate of HP customers on the blocking probabilities for HP, LP, and overall customers. As increases, the blocking probability decreases across all priority levels. This is because the higher block generation rate allows HP customers to be served more frequently, which in turn release the capacity in the customer queue for LP customers. As a result, the probability that LP customers are blocked is reduced. In addition, is smaller than . This is because the capacity limit of the customer queue for the HP customers is no smaller than that for LP customers. Furthermore, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which contributes to a reduction in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑122 illustrates the impact of the block generation rate of HP customers on the system throughputs for HP, LP, and overall customers. As increases, the system throughput increases across all priority levels and then gradually saturates. The rise is primarily contributed by , which increases more significantly due to the release of queue capacity made possible by faster processing of HP blocks. In contrast, eventually approaches a limit determined by . In addition, is smaller than . This is because the customer arrival rate of the HP customers is smaller than that of LP customers. Furthermore, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, reducing effective . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑123 illustrates the impact of the block generation rate of HP customers on the impatience probabilities for HP, LP, and overall customers. As increases, the impatient probability decreases across all priority levels. This trend is mainly due to the faster allowing HP customers to be served more quickly, which indirectly frees up capacity in the system. Consequently, LP customers experience shorter waiting times, reducing their likelihood of reaching their impatience threshold. In addition, is higher than , as LP customers are more likely to experience longer waits due to the non-preemptive priority discipline. As described above, with impatience is larger than without impatience. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure ‑: HP block generation rate vs. average waiting time in the customer queue

Figure ‑: HP block generation rate vs. average waiting time in the block queue

Figure ‑: HP block generation rate vs. average waiting time in the system

Figure ‑: HP block generation rate vs. average number of customers in block queue

Figure ‑: HP block generation rate vs. blocking probability

Figure ‑: HP block generation rate vs. system throughput

Figure ‑: HP block generation rate vs. the impatient probability

### HP Consensus Rate

Figure 5‑124 to Figure 5‑129 show the relationship between various performance metrics and the consensus rate of HP customers . Both simulation results and analytical results are shown for comparison.

Figure 5‑124 illustrates the impact of the consensus rate of HP customers on the average waiting times in the customer queue for HP, LP, and overall customers. As increases, the decreases. The reduction is more pronounced for , while remains relatively stable. This is because higher allows HP blocks to complete consensus more quickly, thereby shortening the duration that HP customers occupy system capacity. As a result, more capacity becomes available for LP customers, so that reducing . In addition, the is much smaller than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue. Furthermore, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which further suppresses queue buildup and contributes to the decline in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑125 illustrates the impact of the consensus rate of HP customers on the average waiting times in the block queue for HP, LP, and overall customers. As increases, the decreases slightly. The decline is primarily contributed by , while remains nearly constant. This is because a higher allows HP blocks to complete consensus more quickly, reducing the amount of time the HP customers spend waiting in the block queue. Since the consensus rate of LP customers is not affected, their waiting time remains unchanged. In addition, at , is noticeably higher than , but the two curves intersect around , after which becomes lower. This crossover occurs because starts lower than the fixed , and increasing improves HP processing speed. Furthermore, with impatience is the same as that without impatience. This is because once a block is formed, impatience mechanism has no effect on it. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑126 illustrates the impact of the consensus rate of HP customers on the average waiting times in the system for HP, LP, and overall customers. As increases, the average waiting time in the system decreases steadily for all priority levels. This is because faster reduces delays in the block queue, thereby improving system efficiency. While also decreases slightly as system capacity is released from HP customers. This trend highlights how improving consensus efficiency for HP customers can enhance overall system flow and reduce and . In addition, the is much smaller than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue. Furthermore, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which further suppresses queue buildup and contributes to the decline in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑127 illustrates the impact of the consensus rate of HP customers on the average numbers of customers in the block queue for HP, LP, and overall customers. As increases, the slightly decreases. This change is mainly driven by a noticeable reduction in , while gradually increases due to the admission of more LP customers as system capacity is released by faster . This reflects how increasing can reduce queue capacity for HP customers while indirectly increasing . In addition, is smaller than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue and is larger than , and therefore more LP customers remain waiting in the customer queue before being batched. Furthermore, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which contributes to a reduction in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑128 illustrates the impact of the consensus rate of HP customers on the blocking probabilities for HP, LP, and overall customers. As increases, the blocking probability decreases across all priority levels. This decline is more significant for HP customers, whose blocks are processed more rapidly with higher , resulting in fewer delays and fewer blocked arrivals. Also, faster processing of HP customers indirectly frees up capacity in the customer queue, reducing the as well. In addition, is smaller than . This is because the capacity limit of the customer queue for the HP customers is no smaller than that for LP customers. Furthermore, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which contributes to a reduction in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑129 illustrates the impact of the consensus rate of HP customers on the system throughputs for HP, LP, and overall customers. As increases, the system throughput increases across all priority levels and then gradually saturates. The rise is primarily contributed by , which increases more significantly due to the release of queue capacity made possible by faster processing of HP blocks. In contrast, eventually approaches a limit determined by . In addition, is smaller than . This is because the customer arrival rate of the HP customers is smaller than that of LP customers. Furthermore, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, reducing effective . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑130 illustrates the impact of the consensus rate of HP customers on the impatience probabilities for HP, LP, and overall customers. As increases, the impatience probability decreases across all priority levels. This is because a higher allows HP blocks to be processed more quickly, releasing system capacity and enabling faster admission of waiting customers. Consequently, customers spend less time in the customer queue, reducing the probability of reaching their impatience threshold. In addition, is higher than , as LP customers are more likely to experience longer waits due to the non-preemptive priority discipline. As described above, with impatience is larger than without impatience. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure ‑: HP consensus rate vs. average waiting time in the customer queue

Figure ‑: HP consensus rate vs. average waiting time in the block queue

Figure ‑: HP consensus rate vs. average waiting time in the system

Figure ‑: HP consensus rate vs. average number of customers in block queue

Figure ‑: HP consensus rate vs. blocking probability

Figure ‑: HP consensus rate vs. system throughput

Figure ‑: HP consensus rate vs. the impatient probability

### Transition Rate (ON to OFF)

Figure 5‑131 to Figure 5‑136 show the relationship between various performance metrics and the transition rate . Both simulation results and analytical results are shown for comparison.

Figure 5‑131 illustrates the impact of the transition rate on the average waiting times in the customer queue for HP, LP, and overall customers. As increases, the average waiting time in the customer queue rises steadily across all priority levels. The increase is more pronounced for LP customers, who are more affected by interruptions in service. This is because more frequent transitions from ON to OFF reduce the availability of block generation service, causing longer queueing delays for arriving customers, especially for customers with lower priority. In addition, the is much smaller than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue. Furthermore, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which further suppresses queue buildup and contributes to the decline in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑132 illustrates the impact of the transition rate on the average waiting times in the block queue for HP, LP, and overall customers. As increases, the average waiting time in the block queue increase steadily across all priority levels. This is because more frequent service interruptions delay consensus processing, resulting in longer waiting times for customer(s) in block queue. This effect is observed for both high- and LP customers, with LP customers experiencing slightly longer delay. In addition, the is smaller than . This is because is larger than . Furthermore, with impatience is the same as that without impatience. This is because once a block is formed, impatience mechanism has no effect on it. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑133 illustrates the impact of the transition rate on the average waiting times in the system for HP, LP, and overall customers. As increases, the average waiting time in the system increase steadily across all priority levels. The increase is more significant for , while increases slightly. This is because more frequent service interruptions caused by transitions to the OFF state reduce overall availability of block generation and consensus service, leading to longer queueing delays for customers in the system. In addition, the is much smaller than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue and is larger than . Furthermore, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which further suppresses queue buildup and contributes to the decline in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑134 illustrates the impact of the transition rate on the average numbers of customers in the block queue for HP, LP, and overall customers. As increases, the average number of customers in the block queue increase steadily across all priority levels. This is because more frequent service interruptions of block generation processing cause more customers to wait in the customer queue while forming batches from the customer queue. In addition, is smaller than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue and is larger than , and therefore more LP customers remain waiting in the customer queue before being batched. Furthermore, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which contributes to a reduction in . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑135 illustrates the impact of the transition rate on the blocking probabilities for HP, LP, and overall customers. As increases, the blocking probability increase steadily across all priority levels. The rise is more pronounced for , while increases at a slower rate. This is because more frequent service interruptions reduce the system’s capacity to process customers, which increases the probability that the customer queue reaches its capacity and causes incoming arrivals to be blocked. In addition, is smaller than . This is because the capacity limit of the customer queue for the HP customers is no smaller than that for LP customers. Furthermore, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, which contributes to a reduction in .Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑136 illustrates the impact of the transition rate on the system throughputs for HP, LP, and overall customers. As increases, the system throughput decreases gradually across all priority levels. This is because more frequent service interruptions reduce the chance for block generation and consensus processing, thereby limiting the rate at which customers are served and ultimately lowering the . The decline is more pronounced for , whose service opportunities are more severely impacted by limited availability, while remains relatively stable. In addition, is smaller than . This is because the customer arrival rate of the HP customers is smaller than that of LP customers. Furthermore, with impatience is smaller than that without impatience. This is because the impatience mechanism causes customers to leave the queue once their impatience threshold is reached, reducing effective . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑137 illustrates the impact of the transition rate on the impatience probabilities for HP, LP, and overall customers. As increases, the impatience probability increase steadily across all priority levels. This is because more frequent service interruptions reduce the effective service availability, causing customers to experience longer waiting times in the customer queue, particularly for LP customers. As a result, are more likely to reach their impatience threshold and leave the system. In addition, is higher than , as LP customers are more likely to experience longer waits due to the non-preemptive priority discipline. As described above, with impatience is larger than without impatience. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure ‑: Transition rate vs. average waiting time in the customer queue in the system

Figure ‑: Transition rate vs. average waiting time in the block queue

Figure ‑: Transition rate vs. average waiting time in the system

Figure ‑: Transition rate vs. average number of customers in block queue

Figure ‑: Transition rate vs. blocking probability

Figure ‑: Transition rate vs. system throughput

Figure ‑: Transition rate vs. the impatient probability

### Impatient Rate

Figure 5‑138 to Figure 5‑143 show the relationship between various performance metrics and the impatient rate . Both simulation results and analytical results are shown for comparison.

Figure 5‑138 illustrates the impact of the impatience rate on the average waiting times in the customer queue for HP, LP, and overall customers. As increases, the average waiting time in the customer queue decreases slightly across all priority levels. This is because higher decreases the likelihood that HP customers will abandon the queue upon reaching their impatience threshold, thereby releasing system capacity and allowing more LP customers to be served. This shortens the overall queue length and reducing the average waiting time in customer queue. In addition, the is much smaller than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑139 illustrates the impact of the impatience rate on the average waiting times in the block queue for HP, LP, and overall customers. As increases, the average waiting time in the block queue decrease steadily across all priority levels. This is because the impatience mechanism only affects customers while they are in the customer queue. Once a block is formed, they are no longer subject to abandonment due to impatience. In addition, the is smaller than . This is because is larger than . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑140 illustrates the impact of the impatience rate on the average waiting times in the system for HP, LP, and overall customers. As increases, the average waiting time in the system decrease steadily across all priority levels. This is because higher increases the likelihood that HP customers will abandon the queue upon reaching their impatience threshold, thereby releasing system capacity and allowing more LP customers to be served. In addition, the is much smaller than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue and is larger than . Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑141 illustrates the impact of the impatience rate on the average numbers of customers in the block queue for HP, LP, and overall customers. As increases, and decreases slightly, and increases gradually. This is because higher makes HP customers more likely abandon the customer queue once they reach their impatience threshold, thereby releasing system capacity for LP customers to be served. As a result, more LP customers are able to form the LP. In addition, is smaller than . This is because the HP customers have non-preemptive priority over LP customers in the customer queue and is larger than , and therefore more LP customers remain waiting in the customer queue before being batched. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑142 illustrates the impact of the the impatience rate on the blocking probabilities for HP, LP, and overall customers. As increases, the blocking probability decrease steadily across all priority levels. This is because higher makes HP customers more likely abandon the customer queue once they reach their impatience threshold, thereby reducing the probability that queue reaches its capacity and triggers blocking. In addition, is smaller than . This is because the capacity limit of the customer queue for the HP customers is no smaller than that for LP customers. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑143 illustrates the impact of the impatience rate on the system throughputs for HP, LP, and overall customers. As increases, gradually decreases, while increases slightly, resulting in an almost stable . This is because a higher ​ causes more HP customers to abandon the system before receiving service, reducing their contribution to throughput. Meanwhile, the released system capacity allows more LP customers to be served, slightly increasing their throughput. In addition, is smaller than . This is because the customer arrival rate of the HP customers is smaller than that of LP customers. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure 5‑144 illustrates the impact of the impatience rate on the impatience probabilities for HP, LP, and overall customers. As increases, rises sharply, while decreases slightly. As a result, more HP customers abandon the queue due to the higher . In contrast, decreases because the early departure of HP customers frees up queue capacity, allowing more LP customers to be served. As described above, with impatience is larger than without impatience. Lastly, a strong agreement is observed between the analytical and simulation results.

Figure ‑: Impatient rate vs. average waiting time in the customer queue in the system

Figure ‑: Impatient rate vs. average waiting time in the block queue

Figure ‑: Impatient rate vs. average waiting time in the system

Figure ‑: Impatient rate vs. average number of customers in block queue

Figure ‑: Impatient rate vs. blocking probability

Figure ‑: Impatient rate vs. system throughput

Figure ‑: Impatient rate vs. the impatient probability

# Conclusion

This research investigates a blockchain-based queuing system that models the transaction process under different combinations of customer priority and impatience, while incorporating ON/OFF operational states that reflect the stochastic availability of block generation and consensus phase. The blockchain queuing system comprises two queues in series: a customer queue, where customers wait to be grouped into a block, and a block queue, where grouped customers await consensus. The system supports a partial batch generation mechanism, allowing up to customers to be grouped at once. The ON/OFF states represent the operational availability of the system; during OFF periods, block generation and consensus are suspended, while arrivals continue. We model four scenarios: (1) single-class customers without impatience, (2) two-class customers without impatience, (3) Single-class customers with impatience, and (4) two-class customers with impatience.

For each scenario, we construct a multi-dimensional Markov chain that captures the state of the system. Balance equations are formulated and solved iteratively until the steady-state probability distribution is obtained. Based on these probabilities, key performance metrics are calculated, including throughput, blocking probability, and average waiting times. To validate our analytical findings, we develop a discrete-event simulation implemented in C++. The simulation strictly adheres to the queuing logic and service discipline of each scenario to ensure consistency with the analytical model.

In conclusion, based on our simulation and analytical results, we have made several interesting observations. First, as increases, initially grows but eventually stabilizes around a constant value. Second, in the priority-based scenarios, remains nearly constant, but increases with but the increase gradually slows down. Third, in scenario 4, decreases with increasing at first, but shows a slight increase when becomes large. Fourth, when increasing in the priority-based scenarios, and remains constant. However, shows a downward trend. Fourth, in the priority-base scenarios, increasing leads to an upward trend in . Lastly, scenarios with impatience leads to improvements in most performance metrics compared to scenarios without impatience. Notably, however, remains unaffected by the impatience rate.

Future research directions include incorporating a more realistic voting mechanism into the consensus phase to better reflect practical blockchain operations. In addition, further extensions may involve optimizing the batch policy dynamically based on the real-time queue state, and enhancing the impatience modeling to capture the total time until departure, including both queueing and consensus delays.

# Reference

[1] S. R. Al-Hafidh and E. H. Al-Hemiary, "Integrating Blockchain With IoT-Edge-Cloud Netwotk for Tracking Offloaded Tasks," 2024 4th International Conference of Science and Information Technology in Smart Administration (ICSINTESA), Balikpapan, Indonesia, 2024, pp. 101-106, doi: 10.1109/ICSINTESA62455.2024. 10747972.

[2] R. A. Memon, J. Li, J. Ahmed, A. Khan, M. I. Nazir, and M. I. Mangrio, "Modeling of Blockchain Based Systems Using Queuing Theory Simulation," *2018 15th International Computer Conference on Wavelet Active Media Technology and Information Processing (ICCWAMTIP)*, Chengdu, China, 2018, pp. 107-111, doi: 10.1109/ICCWAMTIP.2018.8632560.

[3] T. Meng, Y. Zhao, K. Wolter, and C. -Z. Xu, "On Consortium Blockchain Consistency: A Queueing Network Model Approach," IEEE Transactions on Parallel and Distributed Systems, vol. 32, no. 6, pp. 1369-1382, 1 June 2021, doi: 10.1109/TPDS.2021.3049915.

[4] Y. -X. Chang, Q. Wang, Q. -L. Li, Y. Ma, and C. Zhang, "Performance and Reliability Analysis for PBFT-Based Blockchain Systems With Repairable Voting Nodes," IEEE Transactions on Network and Service Management, vol. 21, no. 4, pp. 4039-4060, Aug. 2024, doi: 10.1109/TNSM.2024.3384506.

[5] P. Thakkar, S. Nathan and B. Viswanathan, "Performance Benchmarking and Optimizing Hyperledger Fabric Blockchain Platform," 2018 IEEE 26th International Symposium on Modeling, Analysis, and Simulation of Computer and Telecommu-nication Systems (MASCOTS), Milwaukee, WI, USA, 2018, pp. 264-276, doi: 10.1109/MASCOTS.2018.00034.

[6] Q. -L. Li, Y. -X. Chang, and C. Zhang, "Tree Representation, Growth Rate of Blockchain and Reward Allocation in Ethereum With Multiple Mining Pools," in IEEE Transactions on Network and Service Management, vol. 20, no. 1, pp. 182-200, March 2023, doi: 10.1109/TNSM.2022.3195292.

[7] T. Li, Y. Ren, and J. Xia, “Blockchain Queuing Model with Non-Preemptive Limited-Priority,” *Intell. Automat. Soft Comput.*, vol. 26, no. 5, pp. 1111–1122, 2020.

[8] Q. Li, Y. Ma, J. Ma, and Y. Chang. “Information Theory of Blockchain Systems.” *Lecture Notes in Computer Science*, vol 14462. pp. 443-454,2024

[9] M. S. Peelam, B. K. Chaurasia, A. K. Sharma, V. Chamola and B. Sikdar, "Unlocking the Potential of Interconnected Blockchains: A Comprehensive Study of Cosmos Blockchain Interoperability," IEEE Access, vol. 12, pp. 171753-171776, 2024, doi: 10.1109/ACCESS.2024.3497298.

[10] O. Wu, S. Li, Y. Wang, H. Li, and H. Zhang, "Modeling Cross-blockchain Process Using Queueing Theory: The Case of Cosmos," 2022 IEEE 28th International Conference on Parallel and Distributed Systems (ICPADS), Nanjing, China, 2023, pp. 274-281, doi: 10.1109/ICPADS56603.2022.00043.